# TRACE
Tree Rings in Archaeology,
Climatology and Ecology

# Volume 14

Proceedings of the
DENDROSYMPOSIUM 2015
May 20th – 23rd, 2015 in
Sevilla, Spain

Edited by:
Andrea Hevia, Raúl Sánchez-Salguero, Juan Carlos Linares,
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# Preface

This publication is a result of the 14th TRACE conference (Tree Rings in Archaeology, Climatology and Ecology) organized by the Department Physical, Chemical and Natural Systems of the University Pablo de Olavide (UPO) and the Association for Tree-ring Research (ATR), in collaboration with Pyrenean Institute of Ecology-Spanish National Research Council (IPE-CSIC), University of Barcelona (UB), Forest and Wood Technology Research Centre (CETEMAS) and University of Valladolid (UVa). The TRACE 2015 conference was held on May 20-23, 2015 for the first time in the Iberian Peninsula, in Sevilla, Spain.

TRACE is an initiative of the 'Association of Tree-Ring Research' (ATR) and seeks to strengthen the network and scientific exchange of scientists and students involved in the study of tree rings. It aims to present and discuss novel research and approaches in tree-ring science. The scope of the meeting included all fields of dendrochronology and its application on archaeology, climatology, geomorphology, glaciology, fire history, forest dynamics, ecology, plant anatomy, hydrology and physiology, including the use of stable isotopes.

More than 130 scientists working on tree-ring related topics participated in the conference coming from 27 countries: Algeria, Belgium, Bhutan, Brazil, Bulgaria, Canada, Czech Republic, Finland, France, Germany, India, Italy, Kenya, Morocco, Poland, Portugal, Romania, Russia, Slovenia, Spain, Sweden, Switzerland, The Netherlands, Turkey, United Kingdom and United States. The participants enjoyed 117 presentations, divided between 56 talks and 61 posters, structured in 6 scientific sessions: "Anatomy", "Archaeology", "Chemistry", "Climate", "Ecology", and "More Dendro Topics". Keynote speakers approached brilliantly relevant topics during TRACE: Ulf Büntgen (WSL)- "Frontiers in tree-ring research", J. Julio Camarero (IPE-CSIC) - "A dendroecological approach to forest dieback with emphasis on Mediterranean forests", Paolo Cherubini (WSL) - "From false rings to intra-annual density fluctuations in Mediterranean trees and shrubs: beyond the annual resolution of ecophysiological signals" and Paul Sheppard (LTRR-UofA) - "Dendrochemistry: It's Not As Easy As It Looks (And It Doesn't Look Easy)". We thank all of them for their contribution. An Special mention to the session (Coordinated by Paolo Cherubini) allowed a enlightening discussion for participants on the topic: "Publish or Perish: publishing dendrochronology in the cyberspace".

For the first time in TRACE conferences, 4 pre-courses were organized: "Modelling dendro data and process-based models (Instructors: J.A. Blanco & G. Gea-Izquierdo)", "Methods and applications of radiocarbon and stable isotopes in tree-ring (Instructors: G. Battipaglia & J. Voltas)", "Dendrochemistry and blue reflectance: exploring new tools for tree-ring science (Instructors: A. Buras, R. Kaczka & A. Hevia)", "Wood Anatomy in tree-ring research (H. Gärtner & A. Crivellaro)", and 60 people participated in this learning day. Field trip also was an unique opportunity to visit the southernmost *Abies* species in Europe. We walked through the *Abies pinsapo* in a relict forests in the Biosphere Reserve: "Sierra de Grazalema Natural Park" located in the north east of the province of Cadiz (Andalusia region).

After review, 20 manuscripts are published in this volume, offering an overview of the wide spectrum of different tree-ring research fields covered at TRACE. We would like to thank the authors for contributing to this TRACE volume, and the reviewers whose contributions significantly improved the quality of the submissions.

Enough thanks cannot be expressed to Jose I. Seco (UPO) and Jose A. Merino (UPO) who provided guidance when it was needed as well as adjudicating on those difficult decisions. Also thanks to Jesús, Antonio, Lucia, Rai, Alan and Dani for helping during TRACE conference.

In general, the TRACE2015 conference and proceedings are a credit to a large group of people and everyone should be proud of the outcome.

The organizers of the conference also wish to thank for their financial support the sponsors of TRACE 2015: Beta Analytic Ltd. (United Kingdom), COX (Sweeden), GENEI (Spain), Haglöf (Germany), LI-COR and GEÓNICA (Spain), Regent Instruments Inc. (Canada), Rinntech (Germany), Consejo Social y Facultad de Ciencias Experimentales de la Universidad Pablo de Olavide and Walesch Electronic (Switzerland).Thanks due to collaborators Asociación Española de Ecología Terrestre (AEET), EU COST action STReESS, Parque Natural Sierra de Grazalema, Sevilla Turismo, FSC-España and Fundación Cruzcampo.

We would finally like to thank all participants of TRACE 2015 and hope the Spanish experiences during the conference will provide good memories.

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# SECTION 1

# ARCHAEOLOGY

# Absolute dating of the Roman Road near Bunnik, the Netherlands

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## Introduction

During the first centuries AD the Romans controlled the southern part of the Netherlands.. The *limes,* the northern border of the Roman empire*,* was situated along the (former) rivers dividing the Netherlands in two, from Katwijk at the North Sea coast in the west via Arnhem in the east to Germany (Fig. 1). Along the *limes* an infrastructure with watchtowers, military forts and civil settlements was built. Several locations of the *limes* road of AD 124/125 have been studied dendrochronologically. These studies showed that the wood used to build the infrastructure along the *limes* shared the same felling date but also had a very similar tree ring pattern (Visser & Jansma, 2009). The road near Bunnik was part of the shortest route between the forts Fectio (Vechten) and Levefanum (Wijk bij Duurstede). In the summer of 2013, RAAP Archaeological Consultancy excavated a section of the Roman road near Bunnik-Achterdijk, The Netherlands.
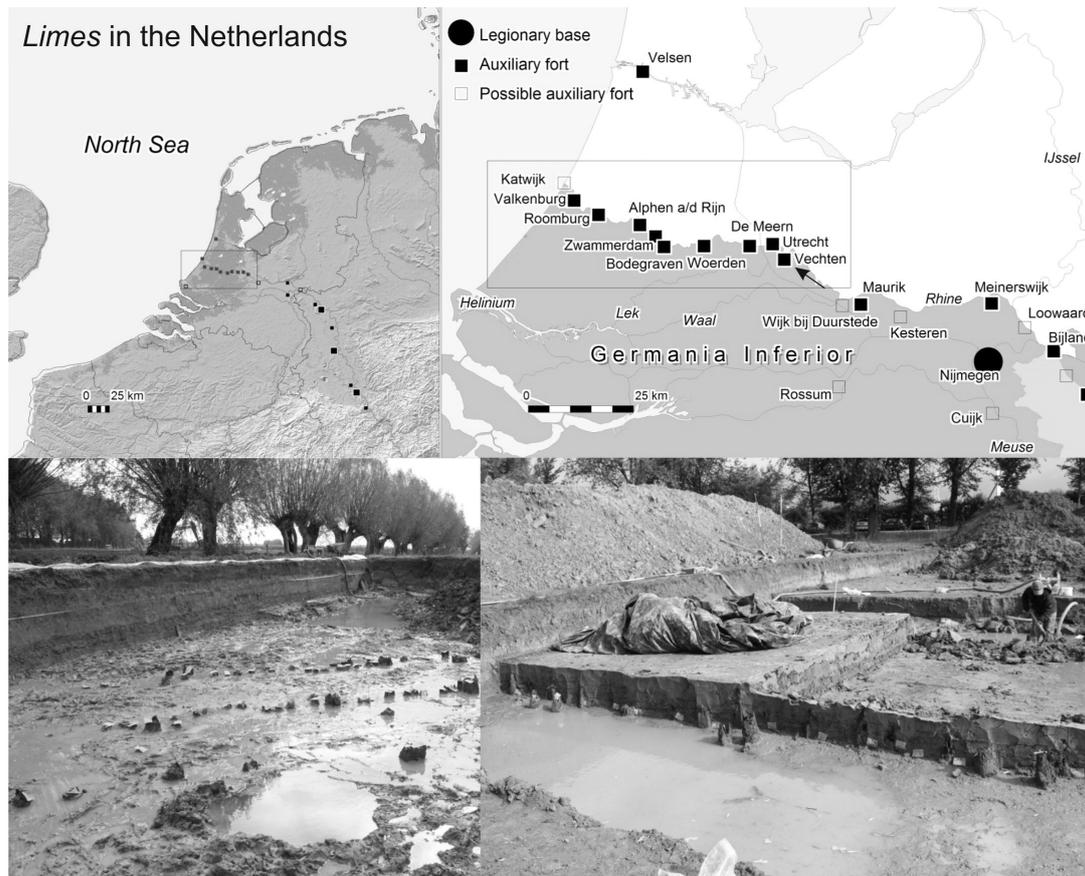


*Figure 1: Top left: Map showing the position of the Limes in the Netherlands (after Polak 2009), top right: map showing the military structures along the Limes, the arrow marks the location of the roman road, bottom left: rows of posts in the ground show the remains of the bridge at the research site, bottom right: remains of the dam in the field at Bunnik-Achterdijk.*

The excavations were commissioned by the Province Utrecht and were necessary due to the construction of a new road. The archaeological site of the Roman road at Achterdijk, Bunnik consisted of the remains of the road structure, including a bridge and a dam. During the excavation around 240 wooden artefacts from the bridge and dam structures were investigated. A large part of the wooden artefacts were posts forming part of a dam holding the road and a wooden construction perpendicular to the road. The latter is interpreted as a bridge. Samples were collected of both the dam and the bridge for dendrochronological research with the purpose of dating and provenancing the wooden posts. This research provides information about the felling date of the timber used for the road and whether this particular section of the *limes* was constructed during a Roman building program. Also, the growth pattern of the tree rings can be used to derive the origin of the used material and gives insight in the Roman building strategy

## Material and methods

All posts and beams were examined to check the wood species, ring count, presence of sapwood or bark edge and tool marks. A total of 31 samples was selected for dendrochronological research, 20 originating from the dam and 11 from the bridge. Five dendrochronological laboratories (BIAX Consult, The Netherlands Centre for Dendrochronology/RING Foundation, Van Daalen Dendrochronologie, Groendirectie Holland and Thünen Institut für Holzforschung) collaborated in producing the results. To derive the age of the Roman road, five samples were already dated in 2013 (Van Daalen 2013). The measurement series of these samples were combined with the additional 26 measurements in follow-up research.

Wood samples were cleaned with a razor blade in order to provide the best view of the tree ring boundaries. If necessary, chalk was applied to enhance the contrast. The widths of the growth rings were measured on a VIAS time table and stereo microscope with a magnification of 10x6.5 to 10x50. The registration is with a resolution of 0.01 mm. The measurements were registered with software program PAST5.0.575 (Knibbe 2014). Depending on their percentage of parallel variation also terme *Gleichläufigkeit* (GLK) and t-value ($t_{Hollstein}$), wood samples with corresponding growth patterns were grouped into tree groups (TS; threshold values t> 10 and GLK> 80) or timber groups (TG; threshold values t> 5 and GLK> 68). Tree groups contain samples which probably originate from the same tree. Timber groups contain samples which originate from the same forest or region. The individual samples, TSs and TG were compared to a large dataset of reference chronologies covering the region of North-West Europe (Jansma 1995, Jansma unpublished, Jansma *et al.* 2014, Domínguez-Delmás *et al.* 2014, Van Lanen *et al.* submitted), ITRDB and the Hollstein site chronologies (Hollstein 1980) in order to obtain an absolute date for the last ring that was measured and to establish wood provenance. If an end date could be obtained and sapwood was present, the felling date of the tree was calculated (Jansma 2007). The significance of the dating was tested by calculating the chance probability based on the number of overlapping rings and *Gleichläufigkeit* of the measurement series with the reference chronology.

## Results

Twenty-two of the 31 wood samples could be dated (Tab. 1). All dated samples were oak (*Quercus*) posts. The dendrochronological results can be divided into two clusters, the dam and the bridge samples.

Six samples of the dam have an end date in the year AD 124 (Fig. 2). The bark edge shows a finalized last ring; therefore the cutting season is autumn or winter, meaning that these trees were cut between October 124 and April 125. Some samples have a slightly earlier end date. One sample has an estimated felling date after AD 51. Tool marks on this post indicate that this timber was re-used in the dam construction, hence explaining the much earlier felling date. One sample has a slightly later end date in the winter of AD 128-129.

*Table 1) Dendrochronological results of Bunnik-Achterdijk. MC = member of MC Bunnik-Achterdijk AD 128, N = number of rings, N(s) = number of sapwood rings, GLK = Gleichläufigkeit, t = t-value, P = significance.*

| sample | keycode | N | N(s) | bark edge | first ring | last ring | reference chronology | Overlap | GLK | t | P | Felling date |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **dam** | | | | | | | | | | | | |
| 278 | BUW00040 (MC) | 177 | . | . | -145 | 32 | Group 57 (Jansma, unpublished) | 173 | 74.8 | 10.4 | 0.000000 | after 51 |
| 279 | 13.076.002 | 69 | 23 | yes | 56 | 124 | NLZWOL01 (Sass Klaassen and Hanraets 2006) | 69 | 75.4 | 5.3 | 0.000012 | autumn/winter 124/125 |
| 280 | 13.076.005 | 113 | 13 | yes | 12 | 124 | NETH013 (Jansma 1995) | 112 | 68.8 | 5.61 | 0.000035 | autumn/winter 124/125 |
| 281 | 13.076.004 (MC) | 103 | . | . | -59 | 44 | NETH013 (Jansma 1995) | 103 | 66 | 6.93 | 0.000582 | after 50 |
| 290 | 13.076.003 | 96 | 11 | . | 24 | 119 | NL338.1.3 (Van Daalen, unpublished) | 96 | 67.2 | 8.77 | 0.000375 | ca. AD 125 (119-138) |
| 291 | BUW00010 (MC) | 129 | . | . | -29 | 100 | Group 57 (Jansma, unpublished) | 129 | 71.7 | 9.53 | 0.000001 | after 116 |
| 417 | 13.076.001 | 83 | 10 | yes | -10 | 73 | NETH009 (Jansma 1995) | 83 | 65.7 | 4.9 | 0.002114 | autumn/winter 73/74 |
| 660 | BUW00030 (MC) | 70 | 10 | . | 54 | 123 | Group 59 (Jansma, unpublished) | 70 | 72.9 | 5.61 | 0.000064 | ca. 130 AD (125-134) |
| 682 | BUW00020 | 79 | 23 | yes | 46 | 124 | Group 57 (Jansma, unpublished) | 79 | 68.4 | 5.98 | 0.000536 | autumn/winter 124/125 |
| 689 | BUW00091 (MC) | 92 | 13 | yes | 33 | 124 | Group 59 (Jansma, unpublished) | 92 | 65.2 | 5.86 | 0.001774 | winter 124/125 |
| 861 | 8610001BC | 90 | 10 | yes | 35 | 124 | Group 59 (Jansma, unpublished) | 90 | 68.1 | 5.47 | 0.000297 | autumn/winter 124/125 |
| 863 | 863002AB | 45 | . | . | 39 | 83 | undated | . | . | . | . | |
| 885 | BUW00051 | 128 | 15 | yes | -5 | 123 | Group 57 (Jansma, unpublished) | 128 | 69.9 | 7.41 | 0.000003 | autumn/winter 123/124 |
| 867 | 8670004A (MC) | 164 | 23 | ? | -36 | 128 | Group 57 (Jansma, unpublished) | 160 | 66.3 | 6.01 | 0.000019 | autumn/winter 128/129 |
| 869 | 8690005A (MC) | 41 | 10 | . | 83 | 123 | Group 42 (Jansma, unpublished) | 41 | 74.4 | 6.1 | 0.000890 | ca. 127 AD (123-131) |
| 870 | 8700006B (MC) | 35 | 16 | yes | 90 | 124 | internal date BUW00080 | 35 | 75.7 | 5.35 | 0.001179 | autumn/winter 124/125 |
| 871 | 87100007A | 46 | . | . | . | . | undated | . | . | . | . | |
| 884 | 8840008B | 99 | 12 | yes | 26 | 124 | Group 59 (Jansma, unpublished) | 99 | 64.6 | 5.51 | 0.001834 | autumn/winter 124/125 |
| 891 | 8910009A | 80 | ja | . | 11 | 90 | Group 59 (Jansma, unpublished) | 80 | 66 | 7.17 | 0.003645 | ca. 108 (103-112) |
| 898 | 8980010A | 65 | ja | . | 44 | 108 | Roman TG(A) (Jansma et al 2014) | 65 | 71.5 | 6.04 | 0.000263 | ca. 125 (120-129) |
| **bridge** | | | | | | | | | | | | |
| 916 | BUW00171 | 41 | . | . | . | . | undated | . | . | . | . | |
| 917 | BUW00141 | 76 | +2 | . | . | . | undated | . | . | . | . | |
| 920 | BUW00131 | 54 | 11 | . | . | . | undated | . | . | . | . | |
| 923 | BUW00120 | 67 | . | . | . | . | undated | . | . | . | . | |
| 927 | BUW00101 | 124 | 12+1 | yes | 25 | 148 | Group 42 (Jansma, unpublished) | 124 | 68.1 | 4.31 | 0.000028 | autumn/winter 149/150 |
| 938 | BUW00080 (MC) | 74 | 11+1 | yes | 51 | 124 | Group 57 (Jansma, unpublished) | 74 | 69.6 | 8.41 | 0.000373 | autumn /winter 124/125 |
| 941 | BUW00060 | 57 | 14+1 | . | 92 | 148 | Group 41 (Jansma, unpublished) | 57 | 73.7 | 4.61 | 0.000173 | ca. 149 (149-153) |
| 959 | BUW00151 | 72 | . | . | . | . | undated | . | . | . | . | |
| 969 | BUW00161 | 43 | . | . | . | . | undated | . | . | . | . | |
| 970 | BUW00110 | 63 | nvt | yes | . | . | undated | . | . | . | . | |
| 978 | BUW00070 | 57 | 22+1 | . | 92 | 148 | NLRom_R (Jansma 1995) | 57 | 71.1 | 3.93 | 0.000721 | ca. 150 (149-151) |
| **groups** | | | | | | | | | | | | |
| . | tree 1 BUW5-SvD3 (MC) | 128 | . | . | -5 | 123 | Group 57 (Jansma, unpublished) | 128 | 72.3 | 9.61 | 0.000000 | |
| . | 060_070_TG | 57 | . | . | 92 | 148 | NLRom_R (Jansma 1995) | 57 | 78.1 | 5.67 | 0.000011 | |
| . | MC 060_070_101_TG | 124 | . | . | 25 | 148 | NLRom_R (Jansma 1995) | 124 | 71.4 | 5.48 | 0.000001 | |
| . | MC Bunnik-Achterdijk | 273 | . | . | -145 | 128 | Ardennes (Van Lanen et al submitted) | 273 | 72.7 | 11.9 | 0.000000 | |

*Table 2: Matrix of t-values of all samples of Bunnik-Achterdijk. The framed values constitute the members of the MC Bunnik-Achterdijk AD 128.*

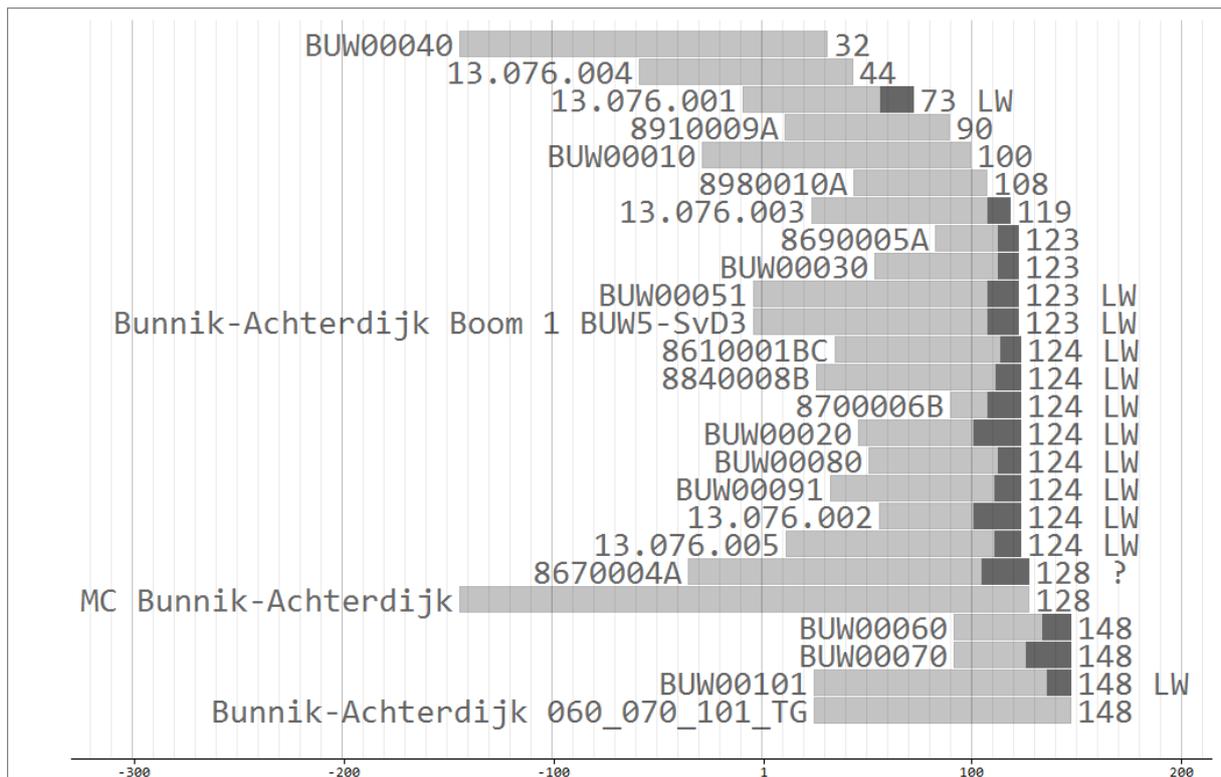| | 13.076.001 | 13.076.002 | 13.076.005 | 8610001BC | 8910009A | 8980010A | BUW00020 | 13.076.004 | 8670004A | 13.076.003 | BUW00051 | BUW00010 | BUW00040 | 8700006B | 8690005A | BUW00030 | BUW00080 | BUW00091 | BUW00101 | 8840008B | BUW00060 | BUW00070 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BUW00070 | 0,0 | 1,5 | 1,1 | -1,0 | 0,0 | 1,1 | 1,5 | 0,0 | 0,7 | 1,9 | 1,1 | -0,5 | 0,0 | 2,0 | 1,7 | 0,4 | 1,9 | 1,6 | 2,4 | 3,4 | 4,7 | ■ |
| BUW00060 | 0,0 | 2,9 | 1,9 | 0,8 | 0,0 | 1,1 | 3,4 | 0,0 | 1,9 | 0,6 | 0,1 | 2,3 | 0,0 | 1,6 | 2,0 | 1,2 | 2,6 | 1,9 | 2,7 | 2,4 | ■ | 4,7 |
| 8840008B | -0,5 | 3,3 | 2,7 | 0,6 | 2,4 | 1,8 | 3,2 | 1,6 | 1,2 | 2,0 | 1,2 | 2,4 | 0,0 | 1,9 | 2,1 | 1,8 | 2,8 | 2,7 | -1,2 | ■ | 2,4 | 3,4 |
| BUW00101 | -0,5 | 1,7 | 1,4 | 1,8 | 0,5 | 0,9 | 2,7 | -0,7 | -0,9 | 1,2 | 1,4 | 1,3 | 2,7 | 1,9 | 4,3 | 3,0 | 3,3 | 1,0 | ■ | -1,2 | 2,7 | 2,4 |
| BUW00091 | 0,7 | 2,4 | 2,4 | 4,3 | 3,0 | 2,0 | 2,5 | -1,3 | 2,4 | 1,6 | 1,8 | 2,5 | 0,0 | 2,6 | 2,5 | 3,5 | 6,3 | ■ | 1,0 | 2,7 | 1,9 | 1,6 |
| BUW00080 | 0,5 | 4,3 | 1,8 | 3,9 | 2,2 | 4,6 | 4,7 | 0,0 | 4,0 | 5,0 | 4,4 | 4,8 | 0,0 | 5,4 | 3,1 | 6,2 | ■ | 6,3 | 3,3 | 2,8 | 2,6 | 1,9 |
| BUW00030 | -1,6 | 2,9 | 0,7 | 1,6 | 1,5 | 1,1 | 2,9 | 0,0 | 1,7 | 3,9 | 4,2 | 2,2 | 0,0 | 3,4 | 5,9 | ■ | 6,2 | 3,5 | 3,0 | 1,8 | 1,2 | 0,4 |
| 8690005A | 0,0 | 2,0 | 2,0 | 1,3 | 0,4 | 0,7 | 3,0 | 0,0 | 1,3 | 3,0 | 2,7 | 1,7 | 0,0 | 2,0 | ■ | 5,9 | 3,1 | 2,5 | 4,3 | 2,1 | 2,0 | 1,7 |
| 8700006B | 0,0 | 2,0 | 1,1 | 1,8 | 0,0 | 0,5 | 1,5 | 0,0 | 0,1 | 2,6 | 4,2 | 1,1 | 0,0 | ■ | 2,0 | 3,4 | 5,4 | 2,6 | 1,9 | 1,9 | 1,6 | 2,0 |
| BUW00040 | 2,1 | 0,0 | 3,1 | 0,0 | 2,6 | 0,0 | 0,0 | 5,6 | 4,6 | -0,4 | 3,7 | 4,4 | ■ | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 2,7 | 0,0 | 0,0 | 0,0 |
| BUW00010 | 2,0 | 2,3 | 4,4 | 4,0 | 1,9 | 3,2 | 3,9 | 5,9 | 5,9 | 7,1 | 4,6 | ■ | 4,4 | 1,1 | 1,7 | 2,2 | 4,8 | 2,5 | 1,3 | 2,4 | 2,3 | -0,5 |
| BUW00051 | 2,8 | 1,0 | 3,9 | 4,5 | 4,5 | 1,5 | 1,2 | 3,6 | 3,6 | 13,5 | ■ | 4,6 | 3,7 | 4,2 | 2,7 | 4,2 | 4,4 | 1,8 | 1,4 | 1,2 | 0,1 | 1,1 |
| 13.076.003 | 1,2 | 2,2 | 2,5 | 3,5 | 3,2 | 1,9 | 2,3 | 3,1 | 3,4 | ■ | 13,5 | 7,1 | -0,4 | 2,6 | 3,0 | 3,9 | 5,0 | 1,6 | 1,2 | 2,0 | 0,6 | 1,9 |
| 8670004A | 1,8 | 1,6 | 1,8 | 1,5 | 1,7 | 2,8 | 1,9 | 4,3 | ■ | 3,4 | 3,6 | 5,9 | 4,6 | 0,1 | 1,3 | 1,7 | 4,0 | 2,4 | -0,9 | 1,2 | 1,9 | 0,7 |
| 13.076.004 | 2,5 | 0,0 | 4,3 | 0,5 | 2,1 | 0,0 | 0,0 | ■ | 4,3 | 3,1 | 3,6 | 5,9 | 5,6 | 0,0 | 0,0 | 0,0 | 0,0 | -1,3 | -0,7 | 1,6 | 0,0 | 0,0 |
| BUW00020 | -1,3 | 3,0 | 3,4 | 3,8 | 2,2 | 5,0 | ■ | 0,0 | 1,9 | 2,3 | 1,2 | 3,9 | 0,0 | 1,5 | 3,0 | 2,9 | 4,7 | 2,5 | 2,7 | 3,2 | 3,4 | 1,5 |
| 8980010A | 1,5 | 3,3 | 3,1 | 2,9 | 2,5 | ■ | 5,0 | 0,0 | 2,8 | 1,9 | 1,5 | 3,2 | 0,0 | 0,5 | 0,7 | 1,1 | 4,6 | 2,0 | 0,9 | 1,8 | 1,1 | 1,1 |
| 8910009A | 1,0 | 0,1 | 4,4 | 5,4 | ■ | 2,5 | 2,2 | 2,1 | 1,7 | 3,2 | 4,5 | 1,9 | 2,6 | 0,0 | 0,4 | 1,5 | 2,2 | 3,0 | 0,5 | 2,4 | 0,0 | 0,0 |
| 8610001BC | 1,8 | 0,7 | 2,8 | ■ | 5,4 | 2,9 | 3,8 | 0,5 | 1,5 | 3,5 | 4,5 | 4,0 | 0,0 | 1,8 | 1,3 | 1,6 | 3,9 | 4,3 | 1,8 | 0,6 | 0,8 | -1,0 |
| 13.076.005 | 1,8 | 1,5 | ■ | 2,8 | 4,4 | 3,1 | 3,4 | 4,3 | 1,8 | 2,5 | 3,9 | 4,4 | 3,1 | 1,1 | 2,0 | 0,7 | 1,8 | 2,4 | 1,4 | 2,7 | 1,9 | 1,1 |
| 13.076.002 | 0,7 | ■ | 1,5 | 0,7 | 0,1 | 3,3 | 3,0 | 0,0 | 1,6 | 2,2 | 1,0 | 2,3 | 0,0 | 2,0 | 2,0 | 2,9 | 4,3 | 2,4 | 1,7 | 3,3 | 2,9 | 1,5 |
| 13.076.001 | ■ | 0,7 | 1,8 | 1,8 | 1,0 | 1,5 | -1,3 | 2,5 | 1,8 | 1,2 | 2,8 | 2,0 | 2,1 | 0,0 | 0,0 | -1,6 | 0,5 | 0,7 | -0,5 | -0,5 | 0 | 0 |

*Figure 2: Range of dated samples including groups of Bunnik-Achterdijk. Sapwood is marked in dark grey, LW = bark edge present.*

Two samples of the dam have a very high agreement and probably originate from the same tree. A site chronology for Bunnik-Achterdijk was created from the timber group consisting of 10 samples (9 of the dam and 1 of the bridge (Tab. 2). The site chronology has a high agreement with reference chronology Ardennes (Van Lanen submitted (Tab. 1 and Fig. 3; t = 11,9, GLK = 72,7, overlap = 273 rings).
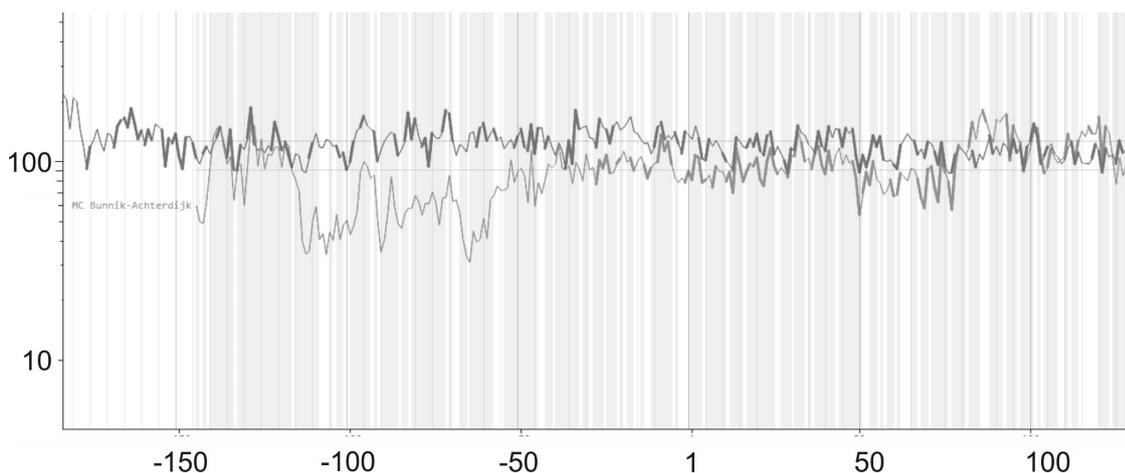


*Figure 3: Visualisation of the match between MC Bunnik-Achterdijk (light grey) with reference chronology Ardennes (Van Lanen et al. submitted; dark grey). Silver grey mark synchronous variations of successive growth rings, t = 11,9, GLK = 72,7, overlap = 273.*

The wood samples of the bridge turned out more difficult to date, only four out of eleven samples were dated. One of these (S938) has a felling date in autumn or winter AD 124-125. The position of this post on the side of the bridge may suggest that it was actually part of the dam construction. This is important because the felling dates of the other three dated samples are in or later than

autumn or winter of AD 149-150. After visual inspection the three samples were grouped in BUW_060_070_101_TG. This group was cross matched with NLRoman_R (Jansma 1995; t = 5,48, GLK = 71,4, overlap = 124 rings).

## Building phase

The felling dates of six posts of the dam indicate that the oak trees were cut down in the autumn or winter of 124-125 AD. Hence, the road was not built before the winter of AD 124-125 AD. This is the same felling date of timber used in the roman roads at Valkenburg, Leidsche Rijn and Woerden (Visser and Jansma 2009). Most likely the road at Bunnik-Achterdijk was built after the winter of AD 124-125, given the more favorable building conditions and that the timber needed to be transported first. One sample has a later felling date in the winter of AD 128-129, possibly indicating that reinforcement was needed shortly after the road was built, or that the entire road was constructed in AD 128-129 or later and that all the timber was stored somewhere before the road works started.

The felling date of AD 124-125 of one post in the bridge may indicate that the bridge was already part of the original road construction. A likely explanation is that the bridge needed reinforcement after the winter of AD 149-150. Another explanation is that the bridge (and possibly the road) was built after AD 149-150 but that an old timber stock was used.

## Provenance

The reference chronologies with which the samples match do not only provide absolute dating but also give information about the provenance of wood. The growth pattern of the samples from the road shows marked similarities with reference chronologies group 57 and group 59 (Jansma unpublished data, Tab. 1 ). A group of 40 independent reference chronologies with regional or site-specific growth characteristics was compiled and the relative strength of the matches (based on t-values) between the site chronology for Bunnik-Achterdijk and reference chronologies was plotted on a map (see Fig. 4).

Reference chronologies with a poorly defined provenance were excluded. This group contains both published chronologies (i.e. Hollstein, 1980; Jansma 1995; Sass-Klaassen and Hanraets 2006; Jansma *et al.* 2014; Van Lanen *et al.* submitted) as well as unpublished chronologies (Tegel; Van Daalen). Differences in sample depth or homogeneity of the material used for the reference chronologies means that the results cannot be compared directly, but nevertheless a clustering of strong results for the Bunnik-Achterdijk chronology with reference material for the Ardennes can be seen. For the remaining samples provenance is more ambiguous since this relied on individual measurements and is in part based on reference chronologies without a well-defined provenance. Sample 8980010A, from the dam section could be dated with calendar Roman TG(A) originating from the Scheldt region in Flanders (Jansma *et al.* 2014). The discrepancy in growth patterns from the samples of the bridge and the samples of the dam clearly shows a difference in origin (t = 1,74, GLK = 58,7, overlap = 104 rings). The individual samples from the bridge match well with reference chronologies which consist of dendrochronological measurements of trees from the levees of the Rhine-Meuse delta(Group 41; Jansma unpublished data); and from the river Vecht region (Group 42; Jansma unpublished data). This means that the timber used in the bridge construction was probably of local origin. In the bridge construction also other wood species such as elm (*Ulmus sp.*) and alder (*Alnus glutinosa Gaertn.)* were used, whereas the dam almost exclusively consisted of *Quercus* posts. This also indicates that local wood was used in the bridge and that the bridge was probably reinforced later than the road.
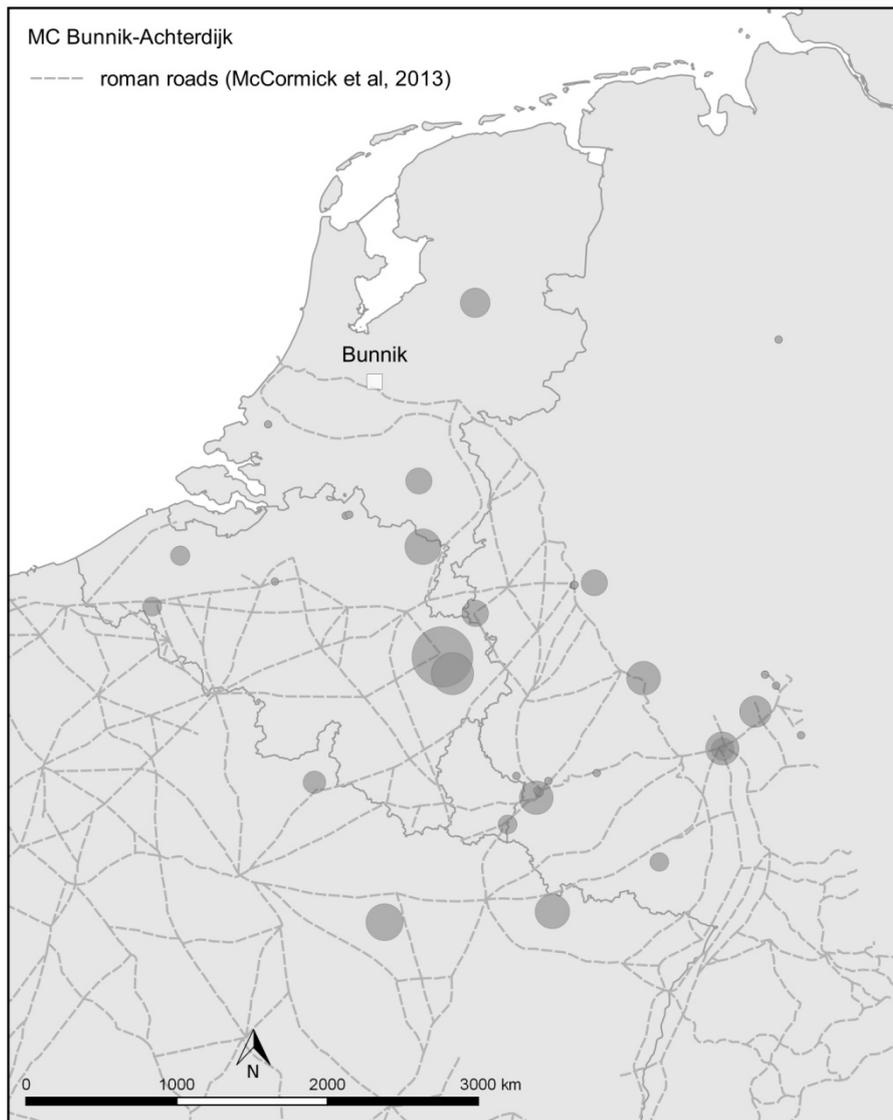
*Figure 4: Geographical map showing the defined provenance of the used reference chronologies. The size of the dot matches the t-value. Big dots show a high correspondence with MC Bunnik-Achterdijk AD 128 pointing to a provenance in the Ardennes.*

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# Roof Frames in the Built Heritage of Brussels (Belgium): The contribution of dendrochronology and written sources

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## Introduction

A three-year multidisciplinary research project began in October 2013, initiated and headed by the Public Service of the Brussels-Capital Region (SPRB), focusing on roof frames in the building heritage of Brussels. The overall aim is to study wooden structures from archaeological, historical and dendrochronological points of view. To more thoroughly understand these structures, specific aspects including description of the typology of roof structures, the wood used and iron elements associated with wooden structures are included in this research.

Nearly one hundred buildings have been analysed, representing a significant dataset in the present-day Brussels-Capital Region, which covers an area of only 161km². The buildings selected represent a range of religious and civil buildings, high status buildings and vernacular architecture. Most are located in the city centre, some in the formerly rural outskirts, now part of the urban territory of Brussels (Figure 1).
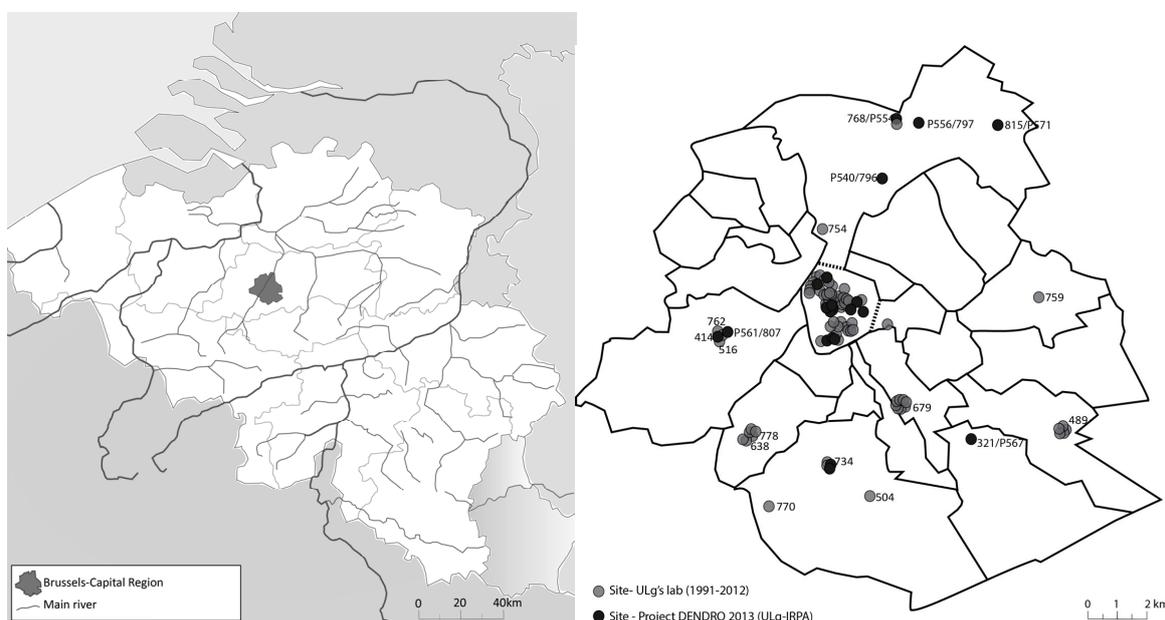


*Figure 1: Left: Location of the Brussels region in present-day Belgium (in dark grey). Right: Location of the sites studied within the administrative limits of the Region.©SPRB*

To achieve this vast project, two Belgian dendrochronology laboratories are collaborating with the Archaeological Service of the Brussels-Capital Region: the University of Liège (ULg) and the Royal Institute for Cultural Heritage, Brussels (KIK-IRPA), with the occasional participation of other collaborators[1].

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The main objective underlying this acquisition of multidisciplinary data is to shed new light on wood working techniques from the 12th-19th century, and on the means of supplying wood for architecture in this specific area.

This paper presents some of the dendrochronological issues of this on-going research with a focus on the complementary work using written sources to better interpret information obtained from the tree rings.

**Materials**

The project was undertaken in the Brussels region and involved buildings of different status, selected in conjunction with rescue and planned archaeology. The dataset is composed mostly of urban houses and also includes private mansions, farms, mills, city halls, churches, religious and industrial buildings.

For a maximal time coverage of the inventory, buildings covering the longest period, i.e., from the 12th-19th century, weresurveyed and analysed.

Depending on the intervention context, which could be prior to renovation, after demolition, or from a perspective of promoting cultural heritage, the conservation state of historical wood was highly variable.

The Brussels beams are generally produced from young, fast-growing trees (almost 80% of the 877 current samples have less than 80 rings and 47% of the oaks have an average ring width of more than 2 mm). These data are however not entirely representative of the wood material used in Brussels roof frames, as the youngest and knottiest trees, less suitable for dendrochronology, were not sampled and are therefore under-represented in this dataset.

Oak (*Quercus robur* or *Q. petraea*) was the most common species (90%), but other species were also exploited. In the remaining 10%, species including elm (*Ulmus* spp.), alder (*Alnus* sp.), poplar (*Populus* spp.), ash (*Fraxinus* spp.), fruit trees (*Prunus* spp.) and conifers (*Pinus sylvetris* L.) have been identified. Such diversity is quite different from other regions in present-day Belgium where oakwas almost exclusively used in roof construction (Hoffsummer 1999), at least until the 19th century which saw an increasing use of Scots pine beams throughout the area.

With respect to such species diversity in Brussels, elm, ash and fruit trees seem to be more frequently found in vernacular architecture and in less urbanized contexts from the 15th to 17th century. This observation should however be refined with further examples. Of note is the fact that different species have sometimes been found in a single wooden structure: oak and elm were used for example in the roof frame of the Church Saint-Nicolas, Neder-Over-Heembeek, and in a townhouse, rue Marché-aux-Herbes8-10 (Figure 2).

The Brussels context reveals another distinctive characteristic: a common practice of re-using well-preserved beams from older buildings. These re-used beams can often be identified, for example by the presence of empty mortises or incoherent carpenter assembly marks. Such elements are not really useful from a chronological point of view, as they no longer document the structure in place, but are still instructive with respect to wood economy and wood supply issues.
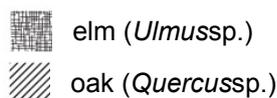
elm (*Ulmus*sp.)

oak (*Quercus*sp.)

*Figure 2 – Truss with oak and elm beams in the roof of the house, Rue Marché-aux-Herbes 8, Brussels.© SPRB*

## Methods

For the dendrochronological sampling, beams with the best dendrochronological potential for dating were selected, i.e., with a substantial number of rings, the fewest growth deformations and the presence of bark or cambium on beams accessible for coring.

Samples were principally obtained using corers[2], but could also be sawn sections when beams had been removed. Samples were sanded[3] and measured[4] in the laboratory. The dating procedure was carried out with the *Dendron-IV* program (Lambert et al. 2005; Lambert 2011).To overcome potential problems in dating, it was crucial to increase the number of samples analysed and, for the most difficult cases, to work in conjunction with other dating methods such as $^{14}$C.

To provide a dendroecological description of the exploited tree populations, cambial age was estimated on cored or sawn samples, in order to evaluate the minimum age of the trees felled. The growth scheme was then compared with models proposed by different authors (e.g., Haneca et al. 2005; Haneca et al. 2006; Girardclos & Petit 2011; Billamboz 2006) to determine the original growing environment of the trees (high forest, coppiced wood, hedges, open environment, etc.).

To identify supply networks, the geographic origin of the wood was determined applying dendro provenancing (e.g.,Schweingruber 1988; Jansma 1995; Bonde et al. 1997;Fraiture 2009) by using European oak chronologies available in both laboratories as well as colleagues' databases in some

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[2] RINNTECH Dry wood borers, 8 mm inside/16 mm outside diameter x 250 mm length, or Schär Core, 10 mm inside / 25 mm outside diameter x 440 mm length.
[3] Papers with grains from 60 to 1200 (CAMI).
[4]*LINTAB$^{TM}$ 6* RINNTECH e.K and *TSAP-Win Professional* (KIK-IRPA) or *MITUTOYO Measurement table* and *dendro Acquisition, Clar M. & Rakka S.* (ULg).

cases. The probable provenance was identified using *t*-values (on maps and in correlation matrices; Fraiture 2013) and Pearson's correlation coefficient (r). However, a constraint was the fact that dendro provenancing provides information only for dated chronologies; therefore, young fast-growing trees were excluded from this research. In parallel to the information obtained directly from tree-rings, archives and written sources were also studied to document local logging to medium-long distance trade.

## Results and Discussion

### *Dating*

Around 400 oak samples have been dated so far, as well as a few beams of Scots pine (around 10).From the first dendro-studies in Brussels in the 1990s[5] until May 2015, around 70 oak site chronologies have been dated for the region (Figure 3) and cover the period AD 1146-1845. However, although the oldest roof dated at present goes back to the end of the 12th century, very few roofs older than the 14th century have been dated. In Brussels, the 'old' conserved wooden roof structures date mainly from the 15th-18th century. Later, roof types changed radically, with the addition of metal structures and prevalent use of conifer wood.

It should be noted that most tree-ring series from Brussels buildings were short (30-50 rings). For instance, in the Saint-Lambert parish church roof (Woluwe Saint-Lambert) a chronology of only 48 rings was built from the five 'best' samples of the site. For this chronology, only a tentative dendrochronological date could be proposed because of the low number of rings, 1194d[6] for the last ring. Radiocarbon dating was done to verify this proposition, providing a date of ca. AD 1040-1220 (890 ± 20BP) for the last ring, with a 95.4% probability (Van Strydonck 2011). This ^{14}C result supports the tentative tree-ring date and it was thus possible to conclude that the trees used to build the roof were felled between 1195d and 1199d, making it the currently oldest known and preserved roof frame for the region. Another extreme example is given by the house with a street-corbelled façade (Rue Saint-Ghislain 86, Brussels), in which only one truss with very fast-growing tree beams was conserved. To date this specific truss typology, one tree-ring sample (40 rings) was cored to be dated by wiggle-matching analysis. The last ring was radiocarbon dated to ca. AD 1445-1485 (357 ± 28BP) with a 95.4%probability (Van Strydonck & Boudin 2015).

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[5] The dendrochronological studies from 1990-2013 were made in the Laboratory of Dendrochronology of the University of Liège (Eeckhout J., Houbrechts D., Hoffsummer P., Maggi C., Weitz A.).
[6] 'd' after a date means that it is a dendrochronological date (Hoffsummer 1989).
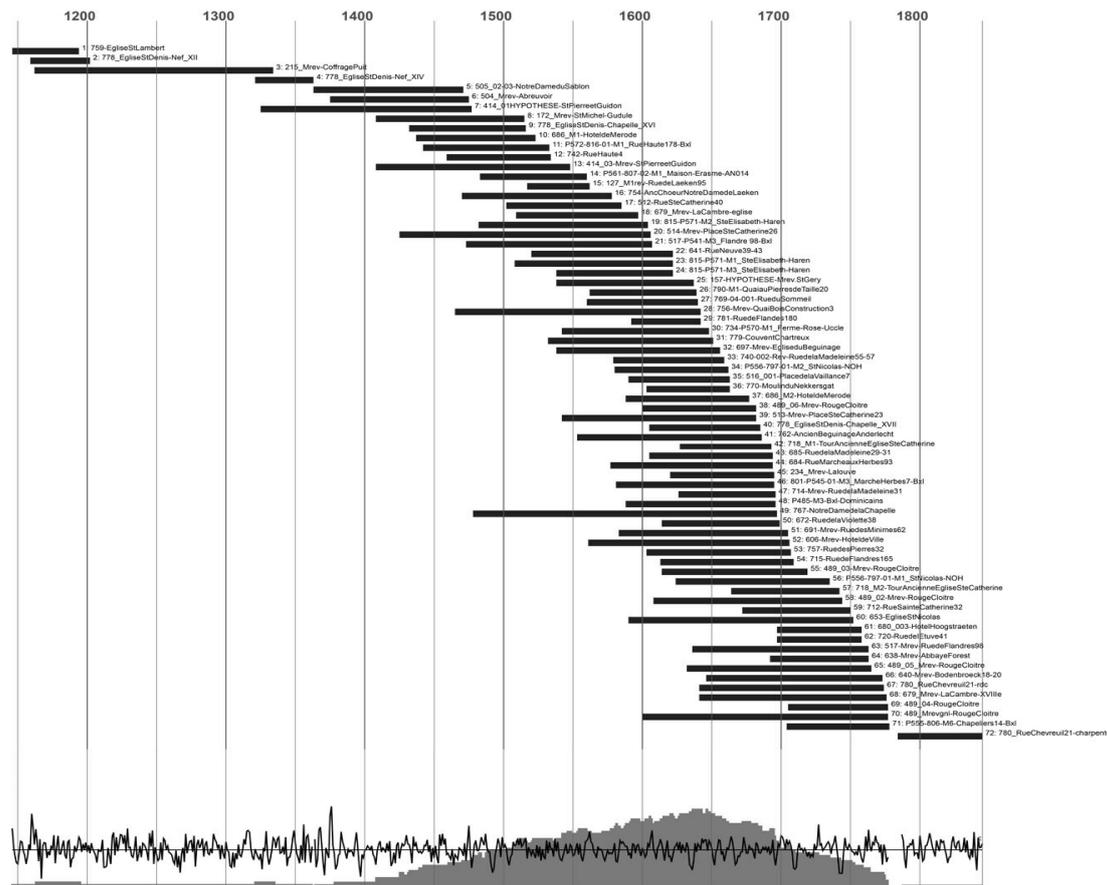
*Figure 3. Dendrochronological bar-graph of the site chronologies available for the Brussels region as of May 2015. © ULg, KIK-IRPA*

## Forest management

Many of the trees examined were young, often with knots or even forks (Figure 4). These features could reflect intense and specific exploitation of local woodlands using coppice-with-standards management. In practice, coppices were exploited with a short cutting cycle, generally less than 30 years, to provide firewood. Second-level vegetation, tall but disseminated trees usually older than 50 years, was used as timber material for building purposes. These tall trees grew during periods without any competition, which caused their rapid and knotty growth.

It should be noted that this part of the research is still in progress: dendrochronological data as well as archives require further in-depth analysis to refine these observations and better perceive the practices exploited in the Brussels region.



*Figure 4 - Example of a fork in a tie beam near the assembly with the rafter.© SPRB*

*Provenance*

The dendrochronological comparisons between the currently dated Brussels site chronologies show clearly distinct groups of data. The chronologies grouped within one of these clusters would be explained as belonging to the same 'dendrochronological *terroir*' (Girardclos, Petit, 2011), for which the interpretation is complex because a 'terroir' involves a combination of several parameters: the geographic provenance itself as well as the type of forest exploitation, the type of soil, etc. On the other hand, for the wood used in buildings, groups that are clearly distinct from each other would in all likelihood reflect different provenance zones.

For softwood joinery work, which requires specific qualities (straight grain, length, etc.), the long-distance importation of wood is attested by dendrochronology at the earliest from the end of the 16th-early 17th century: floorings of the Hotel de Merode were made of Scots pine from Sweden (Fraiture & Crémer 2013, Sosnowska 2013). Nevertheless, it would appear that long-distance trade for construction beams only became common from the 19th century onwards. For this period, tree-ring dating has proved the use of conifer beams that also came from Scandinavia and the Baltic regions. Interestingly, these provenances can be associated with specific merchants' timber marks present on some archaeological woods (Fig. 5). In a warehouse of the Godin factory in Brussels, three beams with merchant's marks were dated (felling between AD 1835-1851d) with the highest correlations with chronologies from central Sweden. This can be associated with the supply area of the Sundswall port (Vandenabeele 2014: 42, *cf*. Demanet 1847). We are currently working on deciphering these marks, which seem to correspond to a complex system of identification of the owners of the timber, its quality, its provenance, etc[7].



*Figure 5. Merchant's timber marks, Godin Factory, Brussels.© SPRB*

Dendrochronology in Brussels also reveals the existence of medium-distance trade: for instance, the Meuse Basin would have been a provenance area for Brussels buildings (100-130 km), as seen in a house on the Rue de Flandre98. Interestingly, other examples of this medium-scale network are depicted in archives, such as the Hainaut forests (Mormal – 120 km from Brussels)which provided beams of exceptional dimensions for the construction of the Aula Magna in the Palace of Coudenberg (Brussels), and La Houssière (50 km from the city) which furnished more common timber for ducal buildings throughout the 15th century (Rochette 1960: 263; Dickstein-Bernard 2007: 56). Unfortunately the wooden structures of the Aula Magna and the ducal buildings did not survive and cannot be sampled.

Next to these long- or medium-scale supply sources, it is known from historical sources that the forest of Soignes and other private woodlands around the city of Brussels were important resources for the urban market (Weitz et al. 2014): their location close to the city ensured low

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[7] For example, L. Vandenabeele, Engineered timber. Appraisal of historic timber roof structures in 19th and early 20thcentury Belgium, PhD in progress, Vrij Univresiteit Brussel.

transport costs (Weitzet al. 2014). Indeed, forest exploitation and commercialisation of the timber products from Soignes are well-documented in written sources from the 15th century onwards. However, identifying local wood in a specific building by dendro provenancing is not an easy task given the lack of chronologies from local living forests extending back to the studied period. In these cases, the combination of historical and dendrochronological data is relevant to increase our knowledge of this local commercial context. For example, in a neoclassical townhouse located Rue Ducaleno. 43 (Brussels), accounts relating to its construction specify the provenance area, revealing that the trees were cut in various woodlands around Brussels, in the domain of Dieleghem Abbey in Jette. The documents also mention the type of forest management ('*raspe sous futaie*', i.e., coppice-with-standards, with a 7-year rotation).Ten samples were collected and dated: the trees were felled between spring 1780d and winter 1780-1781d. Interestingly, in the building itself, the carpenter stamped his name and the date of his work on a beam: 'G. Van. Schepdael. Me fecit. 1781' (Fig. 6). Therefore, this study provides not only a precisely located site chronology for Brussels, but also an example of the rapid use of the trees after felling in the Brussels region.



*Figure 6 – Stamp with name of the carpenter and date of construction on a beam, Rue Ducale 43, Brussels. © SPRB*

## Conclusions

Dated chronologies provide key information to address archaeological questions. At minimum, they allow the buildings themselves to be dated, but also add new dated structures to enlarge the roof 'chrono-typology' database (Hoffsummer 1999, 2002, 2011). They also offer chronological markers for wood working techniques (tools, use of iron reinforcement, etc.). On the whole, the increase in results builds a more complete picture of chronological change in wood utilisation in building archaeology.

The Brussels project involves buildings from a broad range of contexts, providing a valuable dataset with oak as the main material exploited, but with other species also represented. The use of different species in a single structure has only rarely been documented in present-day Belgian buildings, where oak widely dominates. The systematic study of the distribution of the different species would thus provide further information on the wood supply conditions for Brussels.

The poor dendrochronological potential of the trees used often makes dating difficult and requires an increase in the number of samples collected per structure, and sometimes recourse to radiocarbon dating. Nevertheless, at present, around 70 oak chronologies have been dated for the Brussels region, covering the period AD 1146-1845 with the highest representation during the 16th and 17th centuries.

The building structures and the samples collected for dating are also studied to document the carpentry work, the wood resources exploited and the supply networks. Archival investigations complement this approach and allow precision or explanation of some of the dendro- or archaeological observations. For example, dendrochronological analyses demonstrate the

exploitation of supplies from local logging to long-distance trade, while written sources often provide details that allow them to be identified more precisely.

This increasing dendrochronological corpus, alongside further historical research, will lead to better interpretation of both the ecological growing environments and the geographic provenances of the raw material, and then will permit to reconstruct the economic contexts and networks used for supplying construction wood to Brussels.

## Acknowledgements

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# SECTION 2

# CLIMATOLOGY

# Growth-climate relationships of wild service trees on the easternmost range boundary in Poland

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## Introduction

The wild service tree (*Sorbus torminalis* L.) is a species widespread in Europe: from northern Africa through Spain, England to southern Sweden, and from European coasts of the Atlantic to the northern Iran in the East (Roper 1993, Mitchell 1996, Paganova 2007). Appearance of trees of this species is characterized by low densities in small, isolated groups or as scattered individual trees (Demesure-Musch & Oddou-Muratorio 2004, Pyttel et al. 2013). In Polandthe wild service treereaches the north-eastern border of its range. It appears mainly in the western part of Poland, crossing the Vistula riveronly in two forest districts, Kwidzyn and Jamy, which were theinvestigated areas. The wild service tree is considered as a warm-demanding and drought-resistant species (Bednorz 2007, 2010, Szeszycki 2008). This tree species is very rare in Poland; it has been noted in only 84 natural posts and the whole population of trees has been assessed to about 3500 specimens (without seedlings) (Bednorz 2004, 2010). The study was aimed at examining the growth-climate relationships of the wild service tree appearing in its easternmost posts in Poland.

## Methods

The research sites are situated in northern Poland (Fig. 1), in the forest districts Kwidzyn (KW) and Jamy (JM1 and JM2); the only areas of occurrence of the wild service treeon the eastern bank of the Vistula river. Apart from documentation of the sites and trees investigated (Table 1), the field works encompassed taking samples with a Pressler increment borer, at the height of 1.3 m above the ground. The sampling of 78 wild service trees resulted in the total of 91 samples. Measurements of the tree-ring width were made at the accuracy of 0.01 mm, using a stereoscopic binocular microscope, movable measurement table connected with a counter, and the Dendrometer software (Mindur 2000). Altogether 8307 annual growth rings were measured. The samples were cross-dated and the chronology quality was evaluated using the Cofecha program (Holmes 1983, 1994). Then, based on 32 trees (the reason to use for chronology small number of trees – 32 from 78, were missing rings, often 5-6 in one sequence),a regional chronology was constructed. The RES chronology (de-trended, autocorrelation removed) constructed was subjected to the indexation (using a negative exponential curve and autoregressive modelling), in order to eliminate the age trend and to emphasize the annual changeability of the tree-ring widths, using the Arstan program (Cook & Holmes 1986). The expressed population signal (EPS) analysis was used to assess the degree, to which the chronologies of each plot portrayed the perfect hypothetical chronology (Wigley et al. 1984).The chronology constructed was used as a base for dendroclimatological studies: pointer years as well as correlation and response function analyses. Pointer years are concentration of cross-dated event years within a group of trees (Kaennel & Schwiengruber 1995).

*Table 1: Data on the sample trees with age and DBH - diameter at breast height (130 cm).*

| No. oftree | Age (years) | DBH (cm) | No. oftree | Age (years) | DBH (cm) |
|---|---|---|---|---|---|
| JM1 | 118 | 26.4 | JM41 | >140 | 38.9 |
| JM2 | 97 | 37.3 | JM42 | >120 | 38.2 |
| JM3 | >78 | 44.6 | JM43 | >101 | 33.8 |
| JM4 | 82 | 36.3 | JM44 | 204 | 44.6 |
| JM5 | >66 | 37.6 | JM45 | >95 | 43.3 |
| JM6 | 23 | 12.4 | JM46 | 128 | 41.4 |
| JM7 | 91 | 40.5 | JM47 | >120 | 40.8 |
| JM8 | 105 | 37.3 | JM48 | 92 | 43.6 |
| JM9 | >215 | 38.5 | JM49 | 106 | 30.3 |
| JM10 | 118 | 29.9 | JM50 | 108 | 34.4 |
| JM11 | >67 | 41.1 | JM51 | 179 | 64.7 |
| JM12 | 88 | 25.8 | JM52 | >103 | 43.0 |
| JM13 | >76 | 52.9 | JM53 | 131 | 41.4 |
| JM14 | >175 | 74.8 | KW1 | 138 | 22.6 |
| JM15 | >148 | 51.6 | KW2 | 65 | 24.5 |
| JM16 | 148 | 41.1 | KW3 | 111 | 26.0 |
| JM17 | 186 | 39.8 | KW4 | 112 | 27.4 |
| JM18 | >71 | 33.1 | KW5 | >87 | 30.5 |
| JM19 | 172 | 30.3 | KW6 | 98 | 24.6 |
| JM20 | 72 | 19.1 | KW7 | 115 | 33.8 |
| JM21 | >67 | 16.9 | KW8 | 109 | 21.7 |
| JM22 | 105 | 17.8 | KW9 | 107 | 21.0 |
| JM23 | 67 | 18.5 | KW10 | >167 | 39.8 |
| JM24 | 51 | 14.3 | KW11 | 138 | 21.4 |
| JM25 | 76 | 20.1 | KW12 | >117 | 39.6 |
| JM26 | 87 | 21.7 | KW13 | >53 | 40.2 |
| JM27 | 91 | 15.0 | KW14 | 62 | 37.1 |
| JM28 | 60 | 13.7 | KW15 | 99 | 23.0 |
| JM29 | 115 | 18.5 | KW16 | 118 | 30.1 |
| JM30 | >72 | 16.2 | KW17 | 120 | 31.6 |
| JM31 | 96 | 14.7 | KW18 | 105 | 46.8 |
| JM32 | 87 | 15.0 | KW19 | >90 | 21.3 |
| JM33 | 112 | 17.5 | KW20 | 84 | 27.4 |
| JM34 | 85 | 14.7 | KW21 | 80 | 22.5 |
| JM35 | 120 | 24.5 | KW22 | >143 | 50.0 |
| JM36 | 83 | 27.4 | KW23 | >140 | 29.4 |
| JM37 | 109 | 28.7 | KW24 | 180 | 38.9 |
| JM38 | >68 | 30.0 | KW25 | 152 | 30.2 |
| JM39 | >68 | 38.9 | KW26 | 58 | 27.1 |
| JM40 | 106 | 27.4 | | | |

As pointer years were recognized such years, which exhibited the same growth tendency with respect to the neighbouring years (years with consistently narrow and occasionally large rings),

calculated in the TCS program (Walanus 2002) from minimum of 10 trees, with the minimum threshold of 90% unanimity of the incremental reactions. A year characterized by increasing tree-ring width was a positive year (+), whereas a negative year (-) was marked by a reduction in the tree-ring width (Meyer 1997-1998). A response function analysis was performed for 16-month periods (from June of the year preceding growth to September of the year of growth) using the Respo program (Holmes 1983, 1994). Climatic data were obtained from the nearest meteorological station, which is located in Toruń (Fig. 1); the temperature (T) and precipitation (P) from the years 1948-2013, and the insolation (IN) from the years 1966-2000.



*Figure 1: Location of the study sites. Dash-dotted line marks the eastern range limit of Sorbus torminalis in Poland.*

## Results

Minimum DBH for a sampled trees was 12.4 cm (JM6), maximum was 74.8 cm (JM14 –recognized thickest tree of this species in Poland), average DBH was 31.5 cm and standard deviation (ST)– 11.9 cm. Age of trees ranged from 23 years old (JM6) to over 215 years (JM9). For the 25 trees due to the absence of juvenile wood didn't obtain age (Table 1).

*Chronology*

The 110-year chronology STE (*Sorbus torminalis* East), spanning the period 1904-2013, was produced from 32 individual dendrochronological curves (Table 2). The average tree-ring width amounts to 1.8 mm, ranging from 0.07 to 8.87 mm. The Expressed Population Signal (EPS) value, amounts to 0.89, which is above the threshold of 0.85 (Table 2, Wigley et al. 1984).

*Table 2: Selected statistics of measured and indexed wild service tree chronology (STE). SD - standard deviation, 1AC - 1st order autocorrelation, MST - mean sensitivity.*

| Lab. code | No. of years | Time span | No. of samples | Mean tree-ring width (mm) | Measured chronology | | | Residual chronology | | | EPS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | SD | 1AC | MST | SD | 1AC | MST | |
| STE | 110 | 1904-2013 | 32 | 1.80 | 0.945 | 0.705 | 0.360 | 0.206 | 0.009 | 0.2553 | 0.89 |

*Dendroclimatological analyses*

For the chronology STE altogether 48 pointer years were determined, including 30 negative years (-) and 18 positive ones (+). Negative pointer years are: 1910, 1915, 1917, 1921, 1925, 1930, 1935, 1937, 1940, 1944, 1947, 1949, 1952, 1954, 1956, 1963, 1969, 1971, 1973, 1976, 1978, 1983, 1985, 1990, 1992, 1995, 1998, 2000, 2007 and 2012. Positive pointer years are: 1916, 1920, 1926, 1936, 1938, 1945, 1948, 1955, 1957, 1964, 1967, 1974, 1984, 1993, 1999, 2001, 2008 and 2013. Analysis of meteorological conditions in the pointer years pointed at the amount of precipitationas the factor, which determined radial growth of the *Sorbus torminalis* sample trees. Positivepointeryears are convergent with the years, in which the annual rainfall was higher than the multi-year average (537 mm/year for the meteorological station in Toruńin the period 1948-2013). Therainfall was essential in spring and summer months –its deficiency in that period brought about incremental depressions. On the other hand, sufficient supply of the soil withrainwater in that period resulted in formation of wide tree-rings and, in turn,positive pointer years. The temperature in the growth year and the previous one turned out to be of low importance for the process of the annual increment development. In the case of insolation a relationship between the annual sum of the sunny hours in the year of growth and the year preceding it and the tree-ring width could be noted; higher annual values resulted in development of narrower increments. An example of a positive pointer year is the year 1967, characterized by an annual average temperature of 8.7°C, frosty January and quite mild rest of the winter, spring and summer temperatures notdiverging from the average, and warm autumn. The annual precipitation amountedto 700 mm, in most of the months having been above the average (in particular, June was very humid), only in July the rainfall was lower (Fig. 3). The amount of sunny hoursin 1967 and in preceding 1966 wassomewhat lower than the average. In the months: January, February, April, May, August and September the sums were lower than the averagevalues, in the remaining months (particularly in April and June) – higher than the average. An example of a negative pointer year is the year 1992, with an average temperature of 8.9°C, the sum of precipitation of 424 mm, and the insulation on the level of 1665 hours. The winter and beginning of the spring were thermally similar to the average values, the turn of the spring and summer and the summer months were considerably warmer than the average, but the end of the growth season was cooler than the average. In the entire growth season the precipitationwassubstantially below the multi-year average (Fig. 3). In 1991 and 1990 insolation was higher than the average.
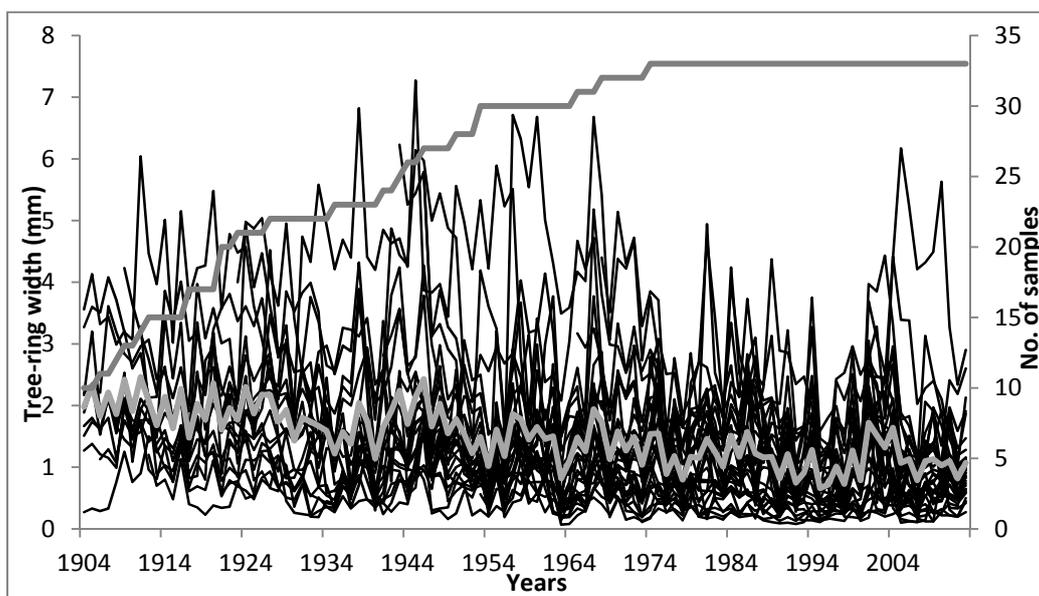


*Figure 2: Tree-ring width series of individual trees (thin black lines) and regional wild service tree chronology - STE (gray line); number of samples in regional chronology (dark gray line).*
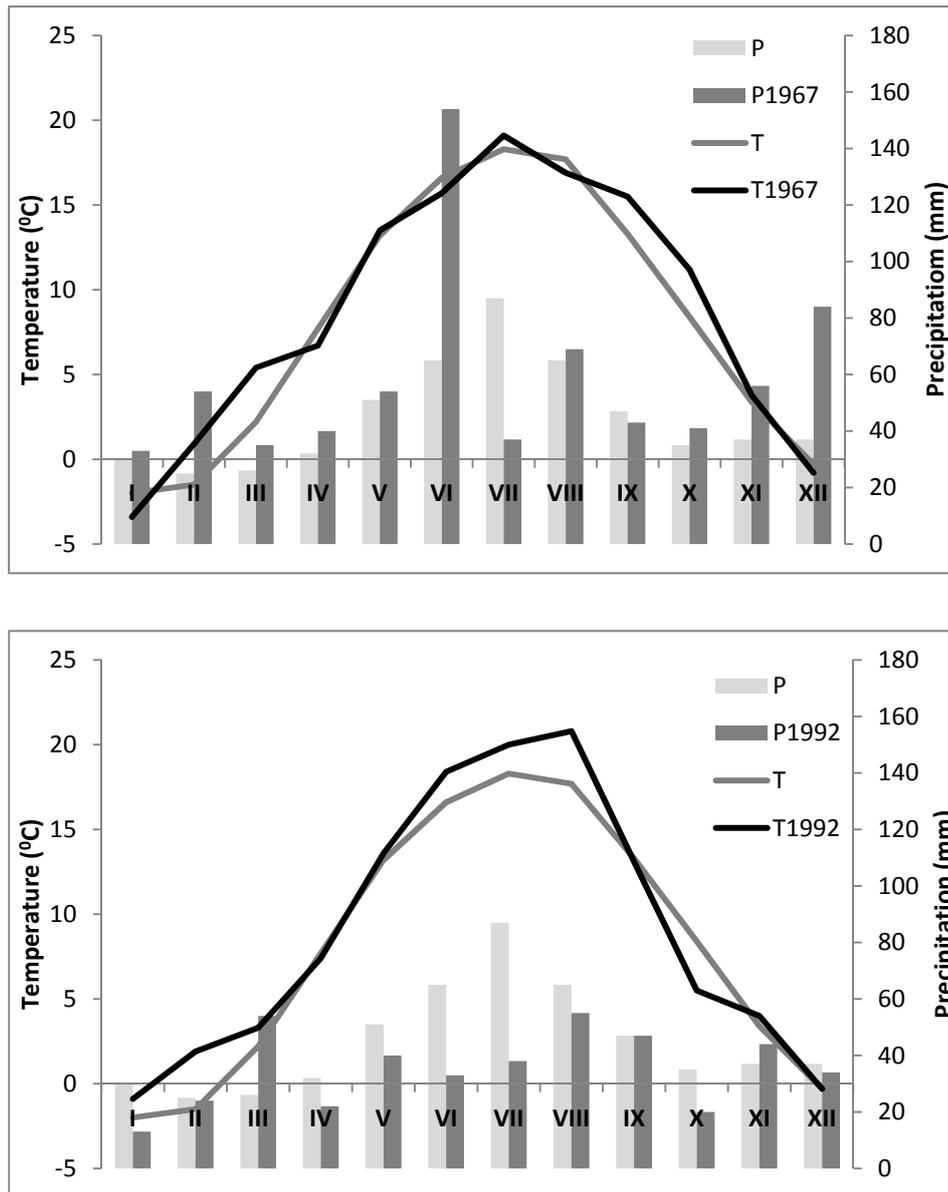
*Figure 3: Mean monthly air temperature (T) and monthly sum of precipitation (P) compared with mean values from 1967 and 1992 years from the Toruń meteorological station.*

Analysis of the correlation and response function also points at the precipitation as the predominating factor conditioning the ring widthof the wild service tree (Fig. 4). For the precipitation the highest rates were noted, as well as most statistically significant values. Also $r^2$ reached very high values. The positive values were prevailing (relationships in the year preceding growth in the months: July, August, October and December, and in the growth year in the months: January, February, May and June). Only for August of the current year negative values of the multiple regression could be noted. The second crucial factor conditioning ring width was the insolation. In this case negative values of correlation and regression predominated (for the year preceding growth in months: July, September and October, and in the current growth season in January and May). Only in September of the current year positive values of the correlation and regression for the amount of sunny hours could be noted (Fig. 4).
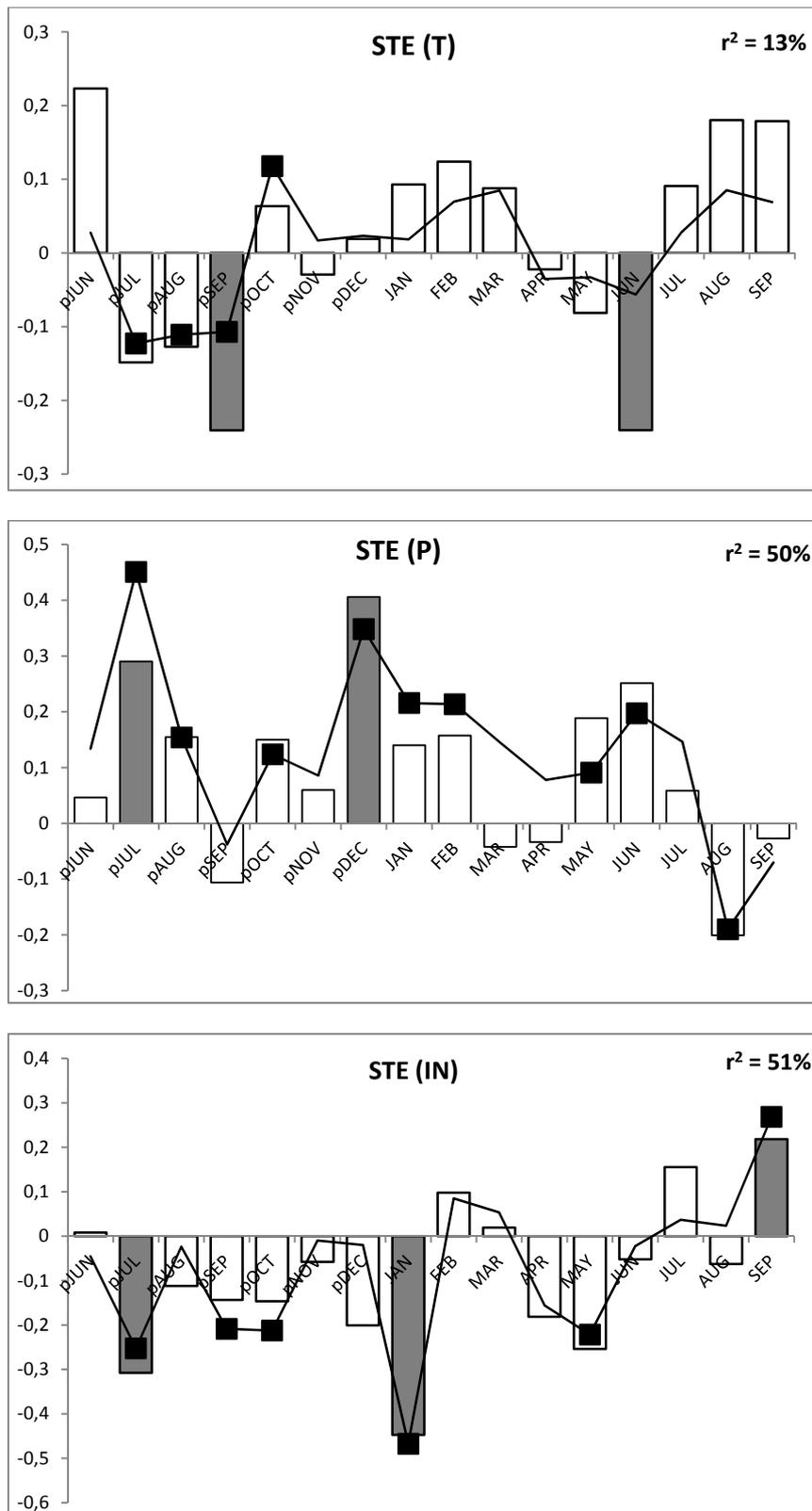
*Figure 4: Results of correlation and response function analyses for regional chronologies and air temperature (T) precipitation (P); and insolation (IN) bars denote correlation coefficients; line represents response function; significant values (α = 0.05) marked as black squares and gray bars; p, previous year.*

The weakest relationships could be observed for the temperature: negative values of the correlation and regression for July, August and September and positive for October of the year preceding growth, and negative values of the correlation for June of the current growth year (Fig. 4).

**Discussion and summary**

Results of the dendroclimatological analyses point at the amount of precipitation as the main determinant of the ring width of the wild service tree on the easternmost sites in Poland. High precipitationin the previous growth season, in the winter period and in the current vegetation season resulted in formation of wide annual increments. In winter months, in which trees are in the resting phase,abundant rains or snowfalls bring about raising the groundwater level and increasing amount of water in the soil in the spring months, in which the demand for water at deciduous trees is very high.

On account of its scarce appearance, this species is a rare object of dendrochronological studies. In Switzerland, Germany and Denmark the annual response of growth width at the wild service tree showed a predominantly negative relation with monthly temperature. High temperature together with low precipitation may thus cause water stress and strongly limit tree-ring width (Rasmussen 2007). In southern Germany the diameter and height growth of *Sorbus torminalis* is related to the canopy position (Pyttelet al. 2011, 2013). Dominant and co-dominant trees are characterized by fast growth in the first decades or even through the entire life of trees. Simultaneously, the trees growing overshadowed prove to be extremely shade tolerant and can survive long periods of intensive competition.

In spite of its rather low economic importance,the wild service treepresentsa valuable admixture in the Europeanforests, increasing their biodiversity. Moreover, in the time of present climatechanges, transformations of the environment, and changes of the tree speciesranges, its ecological and economic value in temperate forests can increase.

**Acknowledgements**

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# Identification of macro-scale groups among 17 site chronologies from Fennoscandia

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## Introduction

The Scandinavian Peninsula provides a continuous and relatively untouched boreal forest which offers an interesting area for dendroclimatic and dendroecological research through its geographical settings and the connected climatic gradients: the latitudinal temperature changes and the longitudinal Luv and Lee effects of the Scandinavian Mountains.

It is generally known that extreme climatic conditions synchronize tree growth, and thus provide a common signal in tree-ring time-series (Fritts 1976). In the boreal forest, tree growth is primarily controlled by summer temperature and direct sunlight (Boisvenue and Running 2006, Büntgen et al. 2011, Esper et al. 2014), thereby providing an ideal area for tree-ring based summer temperature reconstructions of the past centuries (e.g. Eronen et al. 2002, Grudd 2008, Esper et al. 2012). However, with decreasing latitudes the limiting effect of temperature on growth is replaced by increasing sensitivity of the trees to precipitation and water availability (Drobyshev et al. 2011). Next to the latitudinal temperature gradient, a longitudinal effect was displayed in tree-ring stable isotope studies on cloud cover and solar radiation (Young et al. 2012, Loader et al. 2013). Gouirand et al. (2008) also addresses the spatiotemporal relationships of tree-ring based temperature reconstructions in northern Europe. However, a comprehensive study analyzing common growth patterns of the most abundant conifer species Scots pine across Fennoscandia is still missing. An estimation of spatially resolved inter-site relationships would help dividing the Scandinavian Peninsula into ecological habitats with common factors influencing tree growth.

In this study we provide an overview on a comprehensive tree-ring network from Fennoscandia, located between 59°-69°N and 15°-29°E. Overall 17 sites were investigated with similar sampling design (see: Düthorn et al. 2013), allowing comparability among the chronologies. We here address inter-site relationships and expect nearby site chronologies to share variance and contain similar signals. We use multivariate analysis (principle component analysis and hierarchal cluster analysis of variables) as an objective approach to define groups and to present new representative mean chronologies. The same methods were used by Wilson and Hopfmueller (2001) to identify different elevational zones in the Bavarian Forest and by Koprowski (2013) to distinguish climate induced growth patterns in Poland.

## Material & Methods

We compiled a tree-ring width network of 17 Scots pine site chronologies, distributed over northern and eastern Fennoscandia. The spatial arrangement of the sites is clustered in two North-South transects in Finland and Sweden and a longitudinal transect taking the Luv and Lee effects of the Scandinavian Mountains into account (Figure 1).
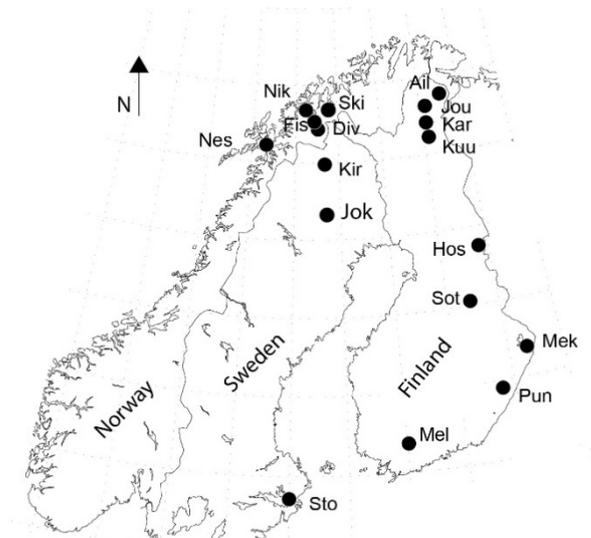
Figure 1: Map showing the 17 sampling sites in Fennoscandia

The age-effect of the tree-ring series was removed using Negative Exponential Curve Standardization after a data adaptive power transformation (Cook & Peters 1997). We calculated residual time-series and stabilized the variance using the Rbar-weighted method (Osborne et al. 1997). After truncating all series at a minimum replication of five series the common period of all site chronologies equals 1882 to 2009.

Two different statistical methods were used to identify homogeneous groups in the dataset: A Principal Component Analysis (PCA) and a hierarchical cluster analysis of variables (HCAv). With HCAv the correlation ratio between the variables(site chronologies) and the center of the cluster, represented by the first Principle Component (PC) of a PCAmix, is calculated (Chavent et al. 2012). Calculations were done with R3.1.1 (R Development Core Team 2014) and the package ClustOfVar (Chavent et al. 2012).

## Results

The PCA approach results inan obvious distinction of the chronologies into two main groups (Figure 2a). Seven chronologies are positively correlated with PC1 and PC2 (group A) and ten chronologies correlate positively with PC1 and negatively with PC2 (group B). Surprisingly, these groups do not show a spatial (longitudinal or latitudinal) pattern (Figure 2b). The southernmost site (Sto), for example, is the only site below the Arctic Circle containing common variance with the northern chronologies(especially sites located in the northeast of the network).The comparison of the site chronologies of the two groups (Figure 2c) reveals that group A chronologies contain a distinct increase in tree-growth at the beginning of the 20$^{th}$ century (1900 to 1930), while this increase is largely missing in the group B chronologies.
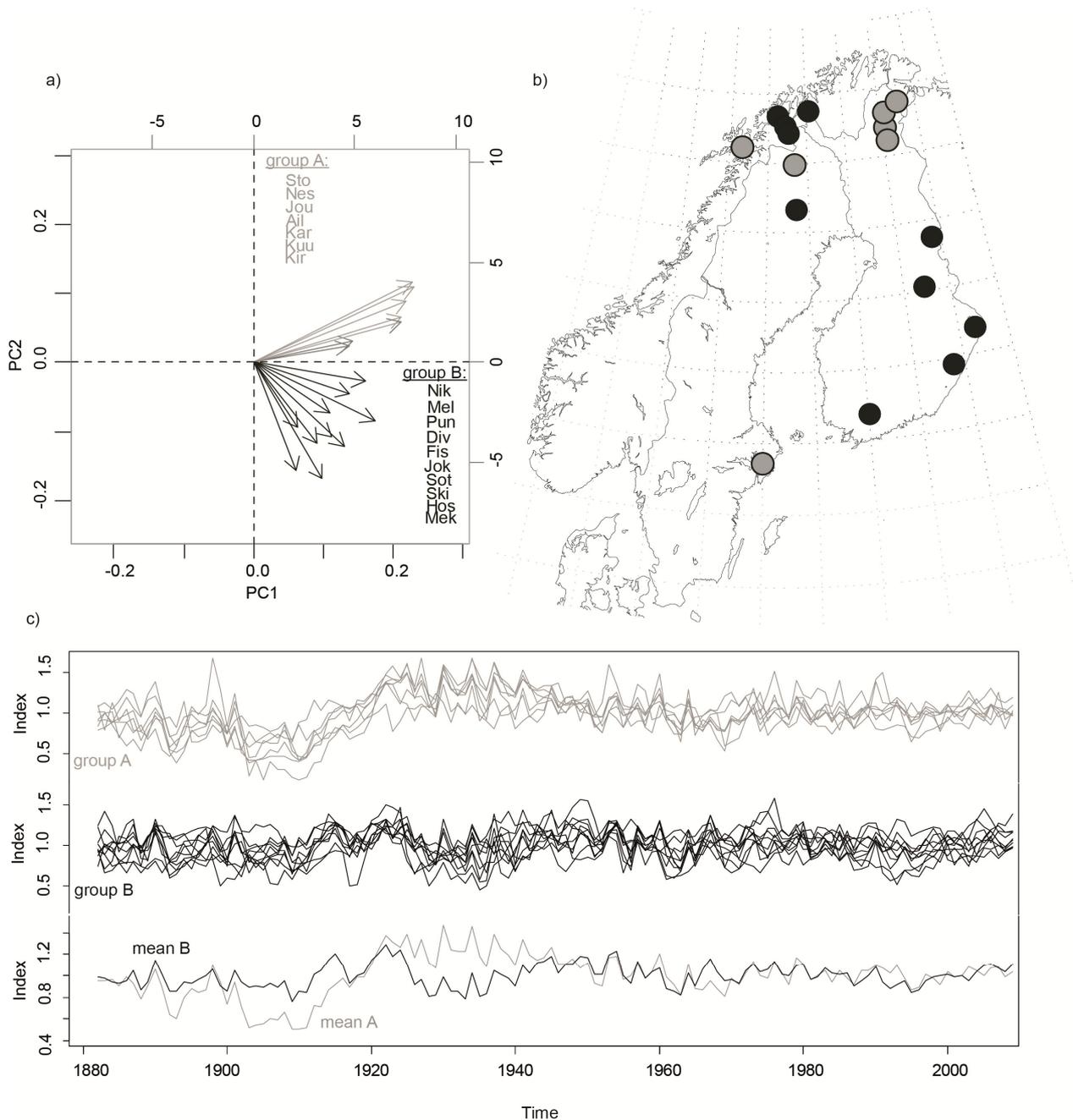
Figure 2: PCA on the Fennoscandian tree-ring network. a) Biplot for PC1 and PC2. Grey (black) arrows belong to group A (B). b) Map showing the spatial distribution of group A (grey) and group B (black) c) Site chronologies of group A (at top), group B (center), and mean chronologies of the respective groups (bottom).

With HCAv two main groups were classified on the first level of the dendrogram (Fig.3a), dividing the data into Northern and Central sites (Fig. 3a &b). Next to these two main groups we could define sub-regions: In the northern parts of Norway and Finland a differentiation of a western and an eastern cluster can be detected, with one cluster being located in the Scandinavian mountain range and the other in the area of Lake Inari in northeastern Finland. Within the second main region (central), two sites in Finland (Sot and Hos) could be separated from the other sites to an own cluster. The classification indicates that the division into three or four clusters offers the most robust results (Fig. 3c).
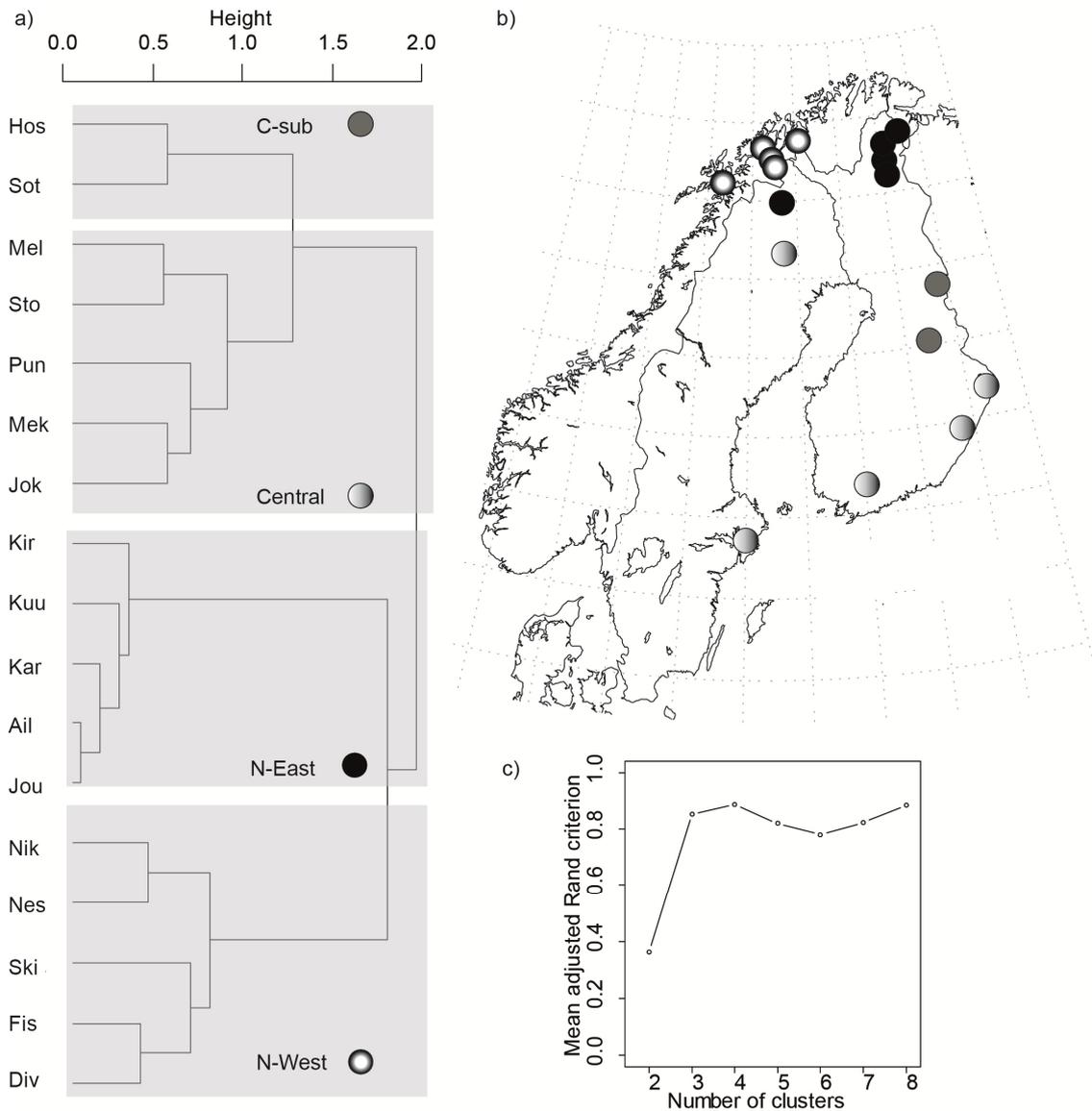
Figure 3:Cluster analysis of the Fennoscandian tree-ring network. a) Dendrogramm for the clustered sections. Grey fields mark the clusters. b) Map showing the spatial distribution of the sites with regard to the clusters.c)Stability of partitions obtained from a hierarchy of 17 variables.

## Discussion

Boreal forest trees are known as being temperature sensitive (Lindholm et al. 2000, Messier et al. 1999)and we expect nearby sites to share variance as summer temperature patterns synchronize tree-growth in space. Düthorn et al. (2015) already displayed that the variance of tree-ring chronologies is related to latitude and might be a good indicator to combine different site chronologies. For assessing common variance among chronologies in more detail, PCA might be a helpful tool(Peters et al. 1981).In our study the PCA helped identifying coherent growth patterns but the method did not support the differentiation of clear spatial clusters. The sites within group A are mainly located in northern Finland but this group also includes the most western (Nes) and southernmost (Sto) sites, i.e. this group contains sites with a distance of up to 1000km in between. However, the difference between groups A and B is defined by the different relationship to PC2.

Since we expected a more pronounced spatial pattern and a grouping of nearby sites, we considered a HCAv which finally provides a clear latitudinal and longitudinal differentiation of the chronologies. The 3-4 clusters from HCAv seem to support the existence of spatially coherent climatic patterns in Fennoscandia. These settings represent the synchronizing aspect of climate ontree-growth. It is generally known that tree growth depends on a variety of external influences

but that these factors can be reduced to one main limiting factor, especially at the altitudinal and latitudinal edge of a species distribution (Fritts 1976). In Scandinavia, we can relate the common influencing factors for the clusters to the latitudinal climate gradient. In the northern area we expect summer temperature as synchronizing factor for tree-growth, while the differentiation in eastern and western chronologies can be associated to the longitudinal position with respect to the Scandinavian Mountains. The sites provide a relatively strict division into Luv (west) and Lee (east) sites. The structure of the central cluster is also very robust and all sites below the Arctic Cycle are combined. The outsourcing of two sites (Hos and Sot) to a fourth group displays that mainly spatially close sites are combined with a higher number of clusters as they should experience similar environmental conditions.

## Conclusion

Cluster analysis of variables is a reasonable tool to emphasize coherency and spatial patterns, and subsequently reduce the dimension and the number of site chronologies as tree-ring series can be averaged to macro-scale chronologies. The approach is also statistically unbiased as the analysis combines different independent methods as inter-site correlations and PCA. This enables a structuring of chronologies in space and can help identifying common influences at the macro-scale.

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# A comparison between Tree-Ring Width and Blue Intensity high and low frequency signals from *Pinus sylvestris* L. from the Central and Northern Scandinavian Mountains

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## Introduction

During the last decades, dendroclimatological methods have been used to produce several climate reconstructions, where chronologies based on maximum latewood density (MXD) data (e.g.,Briffa et al. 2002, Gunnarson et al. 2011, Esper et al. 2012) have provided estimates of past temperature variability. Despite an often superior signal strength of the MXD parameter compared to tree ring width (RW) (e.g., Briffa et al. 2002), very few laboratories in the world use this technique, mainly because this proxy is expensive and labour intensive to produce. As an alternative, blue intensity (BI) utilizing reflected/absorbed blue light from scanned sample-images of tree rings, is explored as a surrogate to radio densitometry (McCarroll et al. 2002, Campbell et al. 2011, Björklund et al. 2014, Rydval et al. 2014). However, BI seems more susceptible to biases caused by the transition between the heartwood and the sapwood, but also by the mixing of modern wood and deadwood (Björklund et al. 2014). This has according to Rydval et al. (2014) and Wilson et al. (2014) restricted the application of the, to the MXD analogue, MXBI parameter (Björklund et al. 2014) to frequencies higher than 20 years. To overcome this bias, Björklund et al. (2014, 2015) suggested the use of a new variant of BI parameter: the adjusted Δblue intensity ($\Delta BI_{adj}$), which is derived by subtracting the BI in the earlywood from the MXBI, after samples have been contrast adjusted, based on their general level of staining (Björklund et al. 2015). Few comparisons between RW and MXD have been made (e.g., Briffa et al. 2002, Franke et al. 2013), and even fewer comparisons between MXBI and RW have been made (Wilson et al. 2014). The aim of this study is to assess the similarities and differences in temperature sensitive *Pinus sylvestris* L. RW and $\Delta BI_{adj}$ chronologies sampled across three sites in Sweden, by exploring 1) the climate correlation and spectral characteristics of the different parameters, 2) the inter correlation and frequency association between them.

## Materials and Methods

We used chronologies from three sites along the Scandinavian Mountains in Sweden:1) Arjeplog, 2) Jämtland (1 and 2 are described in Björklundet al. 2014) and 3) Rogen Nature Reserves. The latter is located close to the border to Norway(62°21'N, 12°26'E) (Fig. 1). The topography is a broken plateau, with gentle slopes and round tops reaching between 1000 to 1200 m a.s.l. (Länsstyrelsen 1993).The mean annual temperature at the sites is 1.3 ºC and the precipitation sums 628 mm year$^{-1}$ (1970-2000 average), at Duved meteorological station, located 400 m a.s.l. and 125 km NE from the site). In 2011, 120samples were collected from both living and dead Scots pine (*Pinus sylvestris* L.) trees in an area of 15square km by the lake Käringsjön in the Rogen Nature Reserve. The samples were glued to wooden strips, and sanded with progressively finer sandpaper (grit 40 to1200). Tree-rings were visually cross dated to their exact year of formation,

and the widths of annual increments were measured with a 1/100 mm precision using a sliding measuring stage connected to the TSAP-Win software (Rinntech). The accuracy of the crossdating was verified statistically in the COFECHA program (Holmes, 1983).For the BI analysis, samples were cut to 4 mm thick laths and refluxed in ethanol for up to 72 hours, then air-dried and sanded again (grit 400 to 1200). The samples were scanned at 1200-1600 dpi resolution (EPSON Perfection 600) using Silver fast AI Professional$^{(TM)}$ calibrated with a colour card IT8 7/2. $\Delta BI_{adj}$ was calculated according to the methods described by Björklund et al. (2015). The $\Delta BI_{adj}$j and the RW chronologies were standardized using a signal-free (Melvin et al. 2008) variant of the regional curve standardization (Briffa et al. 1992) presented in Björklund et al. (2013), called RSFi. The data used for calibration was temperature anomalies averaged over the 55°-70° N and 5°-25° E region from the monthly gridded 5.0° x 5.0° HadCRUT4.3 dataset, spanning from 1850 to present (Fig. 1) (Morice et al. 2012). The temperature response was analyzed using the DendroClim2002 program (Biondi & Waikul, 2002). The stability of the relationship between the proxies (RW and $\Delta BI_{adj}$) and within the proxies was assessed with moving window correlations (50-year window length, 1-year lag). To calculate the coherence, i.e. the frequency dependent association between two time series, the program Anclim (Stepánek 2008) was used.
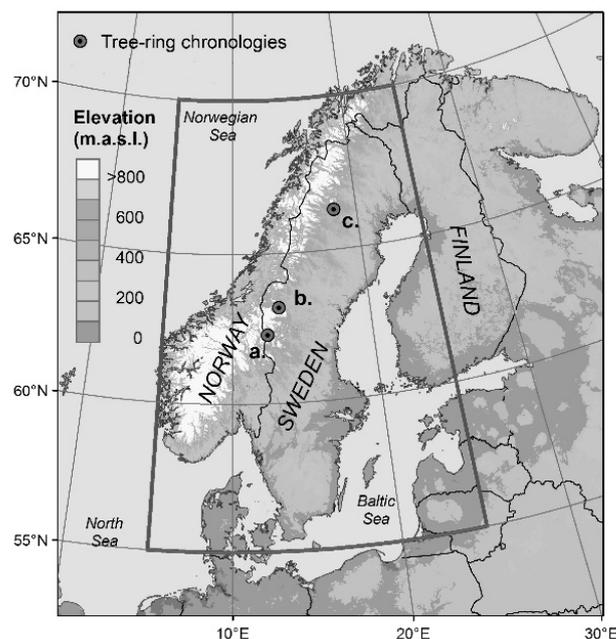


Figure 1: Map over Scandinavia: a, b and c reoresent samppling sites Rogen, Jämtland and Arjeplog respectively. The quadrant area represents gridded HadCRUT 4.3 temperature data (55° to 70° N; 5° to 25° E)

## Results

In the high (inter-annual) frequency domain, both the RW and $\Delta BI_{adj}$ chronologies exhibit strong temperature responses (Fig. 2), where the climate response of $\Delta BI_{adj}$ is generally exceeding that of the RW data in both the length of the target season (March to September) as well as the magnitude of the correlation values. On average, significant correlation ($p<0.05$) values for RW are found with June-August temperatures, but the correlation between $\Delta BI_{adj}$ and June and August temperatures separately, is nearly twice as high as that of RW.
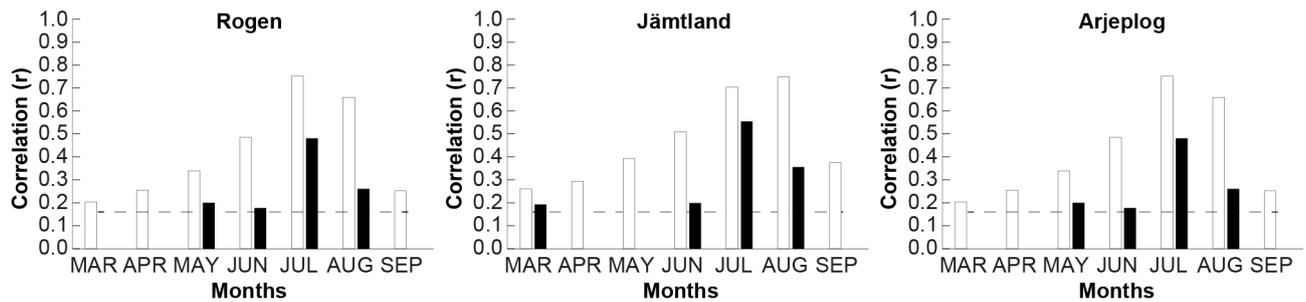
*Figure 2:Significant correlations (p < 0.05; dashed line)between delta blue intensity adjusted (ΔBI$_{adj}$; white bars) and tree-ring width (black bars) from Rogen, Jämtland, and Arjeplog and monthly HadCRUT4.3 temperatures (averaged over the 55° - 70°N and 5° - 25° E region) for the growing season for the period 1850-2010.*

*Table 1: Significant correlations (p<0.05) between tree ring data and theHadCRUT4.3temperature anomalies (averaged from the 55° to 70°N and 5° to 25° E region )averaged over June-August and July.*

|  | Rogen ΔBI$_{adj}$ | Rogen RW | Arjeplog ΔBI$_{adj}$ | Arjeplog RW | Jämtland ΔBI$_{adj}$ | Jämtland RW |
|---|---|---|---|---|---|---|
| HadCRUT 4.3 T JJA | 0.81 | 0.56 | 0.83 | 0.52 | 0.80 | 0.36 |
| HadCRUT 4.3 T July | 0.78 | 0.65 | 0.69 | 0.59 | 0.70 | 0.49 |

The difference in temperature sensitivity and spatial representativity between the ΔBI$_{adj}$ and RW chronologies indicates a higher degree of similarity among parameters than within sites (Table 2). In addition, the relationship between the proxies varies through time as shown in figure 3, with greater correlations between ΔBI$_{adj}$ and RW from 1600 to 1780 and between 1900 and 1950 although prior 1600 the correlation are lower(for ΔBI$_{adj}$, the running correlations were r > 0.6through the whole length of the chronology, while for RW correlations were>0.5 through nearly the whole period, falling below the 0.5 level only between 1450 and 1550).The coherence between RW and ΔBI$_{adj}$ varies across frequencies(Fig. 4),with better coherence at frequencies between 25- and 65-year periods, and decreasing at frequencies <25 years. The coherence between ΔBI$_{adj}$ and temperature data is higher than for RW at all sites (Fig. 5).

*Table 2: Correlation matrix between the two tree-ring parameters and chronologies(significance p<0.05).*

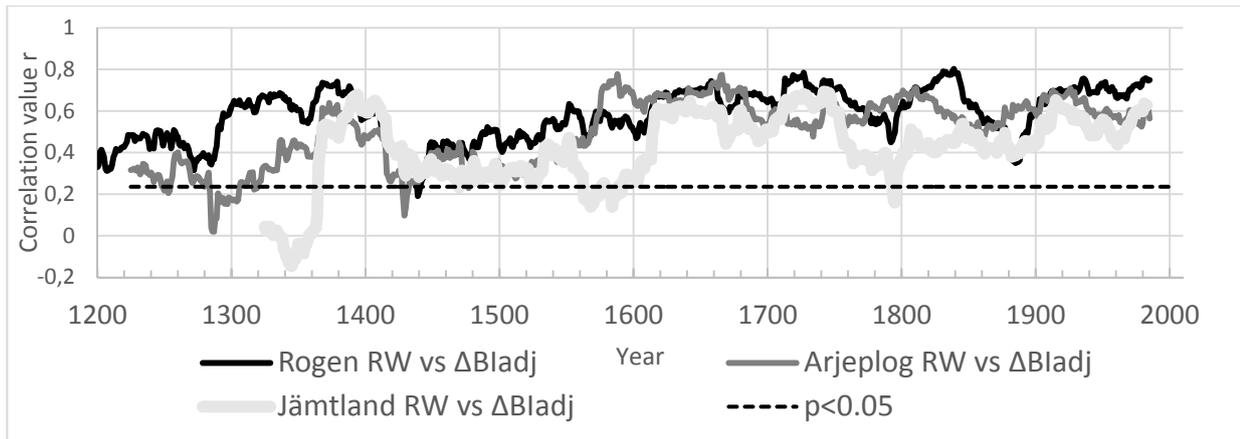|  | Rogen ΔBI$_{adj}$ | Rogen RW | ArjeplogΔBI$_{adj}$ | Arjeplog RW | JämtlandΔBI$_{adj}$ | Jämtland RW |
|---|---|---|---|---|---|---|
| Rogen ΔBI$_{adj}$ | 1.00 |  |  |  |  |  |
| Rogen RW | 0.65 | 1.00 |  |  |  |  |
| ArjeplogΔBI$_{adj}$ | 0.78 | 0.53 | 1.00 |  |  |  |
| Arjeplog RW | 0.50 | 0.67 | 0.60 | 1.00 |  |  |
| JämtlandΔBI$_{adj}$ | 0.90 | 0.53 | 0.79 | 0.41 | 1.00 |  |
| Jämtland RW | 0.56 | 0.80 | 0.49 | 0.63 | 0.48 | 1.00 |

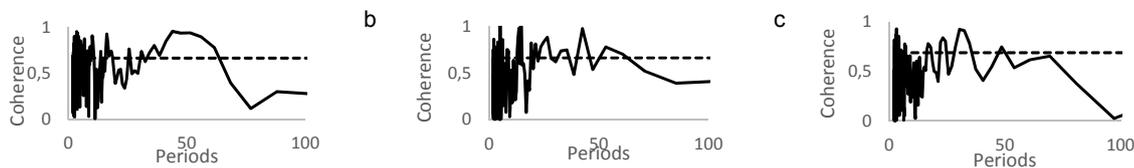*Figure 3:Running correlation (50-year window, 1-year lag) between ΔBIadj chronologies and their corresponding RW versions.*



*Figure 4: Coherence between the ΔBIadj and RW parameters (black lines) from a) Rogen, b) Arjeplog c) Jämtland sites. Dashed lines show the p<0.05 confidence intervals.*
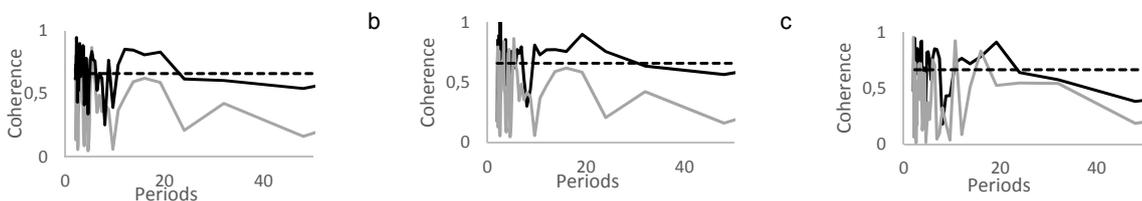


*Figure 5: Coherence between the studied proxies (ΔBIadj = black lines, RW = grey lines)from a) Rogen b) Arjeplog and c) Jämtland and HadCRUT4.3 JJA temperature data Dashed lines show the p<0.05 confidence intervals.*

## Discussion

The comparisons between ΔBIadj and RW in terms of its climate sensitivity gave similar results to those previously reported in comparative studies of MXD and RW (e.g., Briffaet al.1992, Wilson et al. 2014, Esper et al. 2015).We showed that the ΔBIadj parameter possesses a stronger and seasonally longer correlation window with regional temperatures than itsRW counterpart. We further revealed that while the ΔBIadj temperature signal and the intercorrelation between the ΔBIadj chronologies are consistent across time and space, the correlations between RW and ΔBIadj are not, suggesting that the two proxies may not record entirely the same information (Fig. 3). Possibly additional influences on tree growth, such as precipitation, or local site conditions causes the periodical decoupling between the two proxies, and most likely changes in temperature sensitivity affect RW more than BI. Several studies have suggested that there isa memory effect in the RW proxy, where information from one year can be carried over for one or more years (Franke et al. 2013, Esper et al. 2015, Bunde et al. 2013, Schneider et al. 2015), which could cause a decoupling from ΔBIadj. This is suggested by the changes in coherence through frequencies between the proxies (Figs. 3 and 4) and the lower temperature responses. But we cannot conclusively find evidence of this in either of the analyses.

The coherence analysis, however, reveals that at the lower frequencies, both proxies follow each other relatively well with correlations of 0.73, 0.23 and 0.65 (Rogen, Jämtland and Arjeplog, respectively). The coherences between RW and $\Delta BI_{adj}$ indicates that they contain similar information at periods of about 20 and 60 years, implying that these proxies may be combined to investigate climate variability on those frequencies, while care should be taken when looking at other frequencies if they are combined. Also, the fact that the relationship between RW and $\Delta BI_{adj}$ changes through time, adds difficulties to interpretations of reconstructions made using a combination of these parameters derived from Scots pine growing across the sites investigated in this study. For example, exploratory testing showed that composite chronologies of $\Delta BI_{adj}$ and RW from each site in our network were able to explain 15-20 % less of the variance in the regional temperature history, compared to what was derived from the $\Delta BI_{adj}$ parameter alone (results not shown here). While the coherence between $\Delta BI_{adj}$ and temperature revealed clear patters across our three sites, the coherency between combinations of RW-$\Delta BI_{adj}$ and the temperature showed less consistency across sites (i.e. Rogen decreased in all frequencies, Arjeplog maintained the level of coherency at the maximum peak but narrowed from 16 to 24-year cycles to 16 to 19-yearcycles, and for frequencies lower than that range the coherence dropped below significance, and Jämtland improved at 30-year cycles). Another approach could be to combine band pass filtered chronologies from RW and $\Delta BI_{adj}$, where the best frequencies from both parameters are used (cf. Wilson et al. 2014), but then little information from RW would anyway be used. Although not explicitly tested, the differences between the sites and methodologies are also a result from for example, sampling design, sample depth and will also affect the characteristics and relationships of these proxies at different frequencies.

## Conclusions

Here we present similarities and differences between thetree-ring width (RW) and adjusted $\Delta$blue intensity ($\Delta BI_{adj}$) parameters derived from three Scots pine chronologies in central and northern Sweden. Our results suggest that the $\Delta BI_{adj}$ parameter has better skill to portray temperature variability than RW at all frequency ranges. We also show that although RW and $\Delta BI_{adj}$ have significant coherence between 20 to 60-year cycles, the relationship between these proxies is unstable through time, implying differences in climate sensitivity.

## Aknowledges

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# DendroCorr – a simple and powerful software to calculate the growth\climate response

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## Introduction

The determination of the relationship between tree-ring proxies (tree ring width, density, blue reflectance, etc.) and climatic and/or hydrological data are integral part of dendroclimatological and dendrohydrological investigations. There are many programs available that include this application, e.g. RES, included in the Dendrochronology Program Library (Holmes 1992), Precon 5.1 (Fritts 1999), DENDROCLIM 2002 (Biondi & Waikul 2004), and the package 'bootRes' in R (Zang 2012), but they demand some advanced degree of inside or skills (e.g. programming) to use them. Moreover, some of the existing programs require dendro and/or climate data files in special formats, and not all of them produce graphs with correlation results. Using these programs requires preparing data files to the needs of a given software and transforming data from one format into another. Although various statistical tools and software solutions exist, a simple tool, which allows the calculation and visualisation of basic Pearson correlation coefficients is still lacking.
Here we present such a program for calculating correlation coefficients between chronologies (or individual series) and climate/hydrological data.

## DendroCorr

DendroCorr can be used on any OS (Windows, Mac, Unix, etc.). The acronym explains the basic functionalities - using DENDROchronological data to compute CORRelations with climatic time series. Program reads several formats of tree ring measurements used by the dendrochronologists and stored in the International Tree-Ring Data Bank (ITRDB, Grissino-Mayer & Fritts 1997) including *Tucson decadal*, and *Arstan output files*. DendroCorr works with monthly instrumental and gridded data (*dat.txt), which are commonly used by the researchers (e.g. Esper et al. 2007, Wilson et al. 2007, Briffa et al. 2008, Büntgen et al. 2010, Seim et al. 2012). Adapting the software to the most widely used dendrochronological and climate data formats creates the advantage of using DendroCorr in a very fast and easy way. DendroCorr is also able to read formats of the other time series data including NDVI, emission data etc.
DendroCorr is written in Java language. It is built with its most recent version i.e. Java SE 8. Swing lightweight components are responsible for UI, logic uses a number of open source libraries such as Apache Commons, Apache POI, Dom4j. The program can run on all platforms as a .jar file.
DendroCorr is still under development and future versions are anticipated.
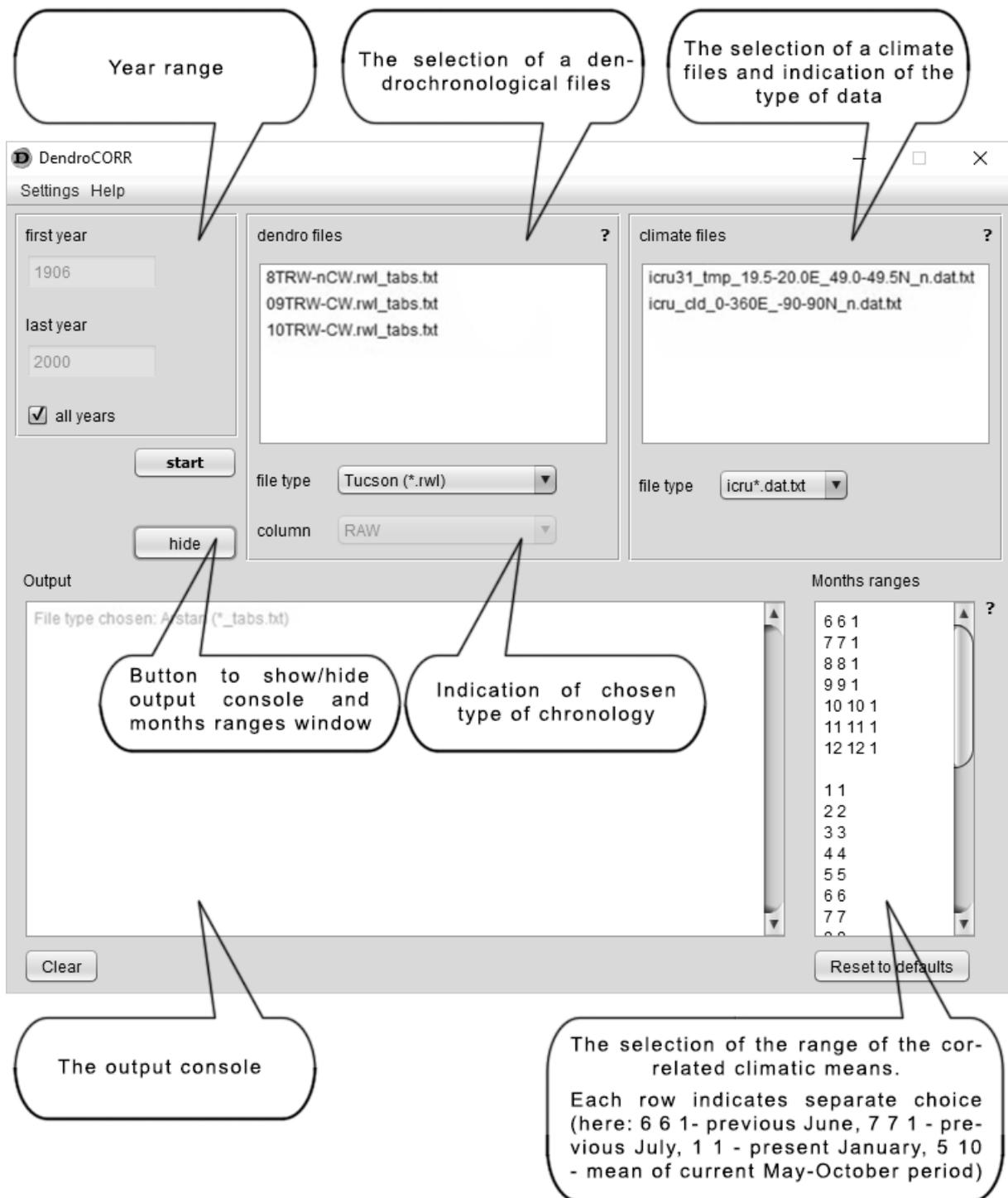
## The use of DendroCorr



*Figure 1: DendroCorr user interface.*

Only a few steps are required to obtain results. First, choose the tree-ring and climate data files by a simple drag and drop. Multiple files of the same format may be used for both dendrochronological and climate data. At the present stage of DendroCorr development, two kinds of inputs of tree-ring data files can be used: i) Tucson decadal file (*.rwl, *.tuc, *.dec, *.txt) and ii) Arstan output file (*.rwl_tab.txt, *rwl_ind1.txt). The user can choose between different kinds of Arstan chronologies (raw, std, res, ars) (Fig. 1) and define the length of the time series over which the correlation should be computed. If the *all years* option is enabled (Fig. 1), the program will use

the widest common range of years between tree-ring and climate data automatically truncated to the period with minimum 5 series according to the second column of Arstan output file: *.rwl_tab.txt.. There is no general limitation for the number and combination of periods of climate data used for calculation of correlations, including previous years months and seasons. The so-called *months range* window allows setting up these parameters (Fig. 1). For example, default settings cover means values from previous year May till recent year October and additionally seven seasonal means (January-March, April-June, April-September, June-July, etc.). Both months ranges window and output window are hidden by default. They become visible upon clicking the *expand/hide* button (Fig. 1). It is also possible to set how detailed the output information is. It may be fully descriptive or turned off to increase the calculation speed.

The computation process is very fast and numerical results are instantly displayed in the output window. The results may be also saved to a MS Excel Macro-Enabled Workbook (.xlsm). The Excel file includes a macro, which may generate charts for all the correlations (supported in MS Excel 2013 and newer). Pressing the *Generate charts* button inside the Excel file will start the macro. A simplified manual regarding each section of the program is also available upon hovering the mouse over the question mark symbol.

The program is able to compute unlimited numbers of correlations during one run, and is available in two languages: English and Polish. The software is free and can be downloaded at: www.pracowania-dendrochronologiczna.pl.

There is no known event of DendroCorr freezing or crashing, which proves it to be a highly reliable program. However, there is a built-in logging system, which provides the user with information about all warnings and errors which may happen during execution. Thanks to this feature the user can pinpoint any reasons for uncompleted calculations (i.e. incompatible input files) or report serious program issues to developers.

## The example of DendroCorr employment

The use of DendroCorr is especially recommended when multiple analyses are needed to identify the character and strength of growth/climate response. These computations are part of e.g. the individual tree analyses approach (Carrer 2011, Rozas 2015).

To present DendroCorr capabilities, the correlation with temperature and precipitation data were performed using 122 scot pines from the Tatra Mountains, Poland. The TRW measurements series were crossdated visually (CDendro) and statistically (Cofecha software, Holmes 1983). Using Arstan program (Cook 1985) residual chronology composed by all 122 trees was established. The individual indexed series were also calculated. The cubic smoothing spline detrending with 50% frequency-response cutoff at 100 years was used in both cases. For climate/growth analysis, the instrumental data from the nearest meteorological station in Zakopane were used. Pearson correlations were computed over the period 1906-2000 using the chronology as well as the individual tree-ring series.

The studied chronology exhibits correlations with summer temperature ranging from 0.39 for July, to 0.32 for June-July, and 0.29 for June-August (all $p<0.01$) (Fig. 2). Correlations with precipitation are all statistically insignificant. These results raise the question if the selection of the trees showing the highest individual relation to climate would lead to an improved  the results (Carrer 2011).

Based on the correlation results of single trees, only those individuals revealing the highest and significant ($p<0.01$) correlations with June were selected and a new chronology constituted of 38 trees was built with the use of the same detrending method. Thereafter the new chronology was correlated with climate data (Fig. 3).
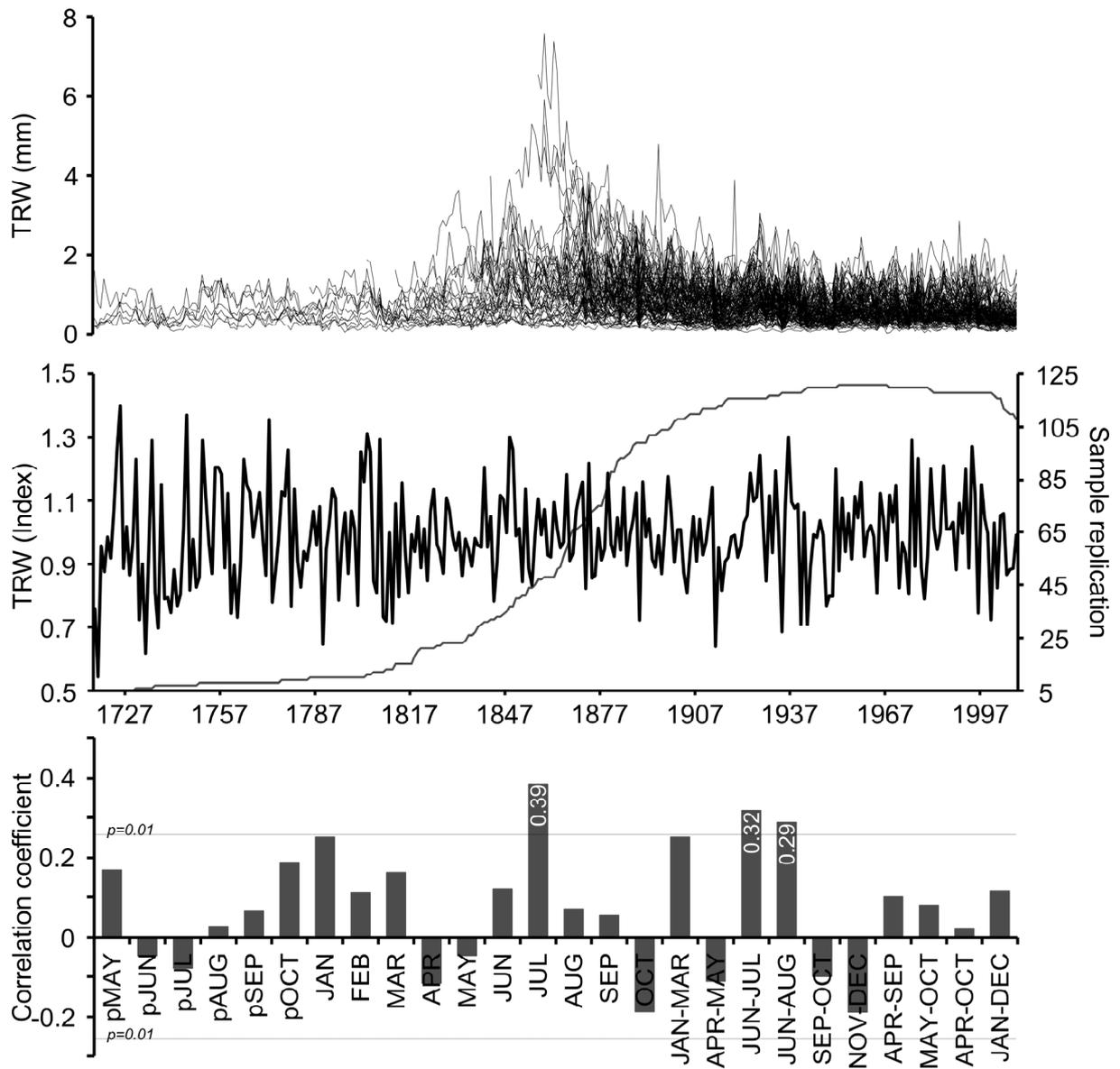
*Figure 2: Spaghetti plot for 122 tree-ring width measurements, the TRW residual chronology built using all 122 TRW series and correlation coefficient results for TRW chronology.*
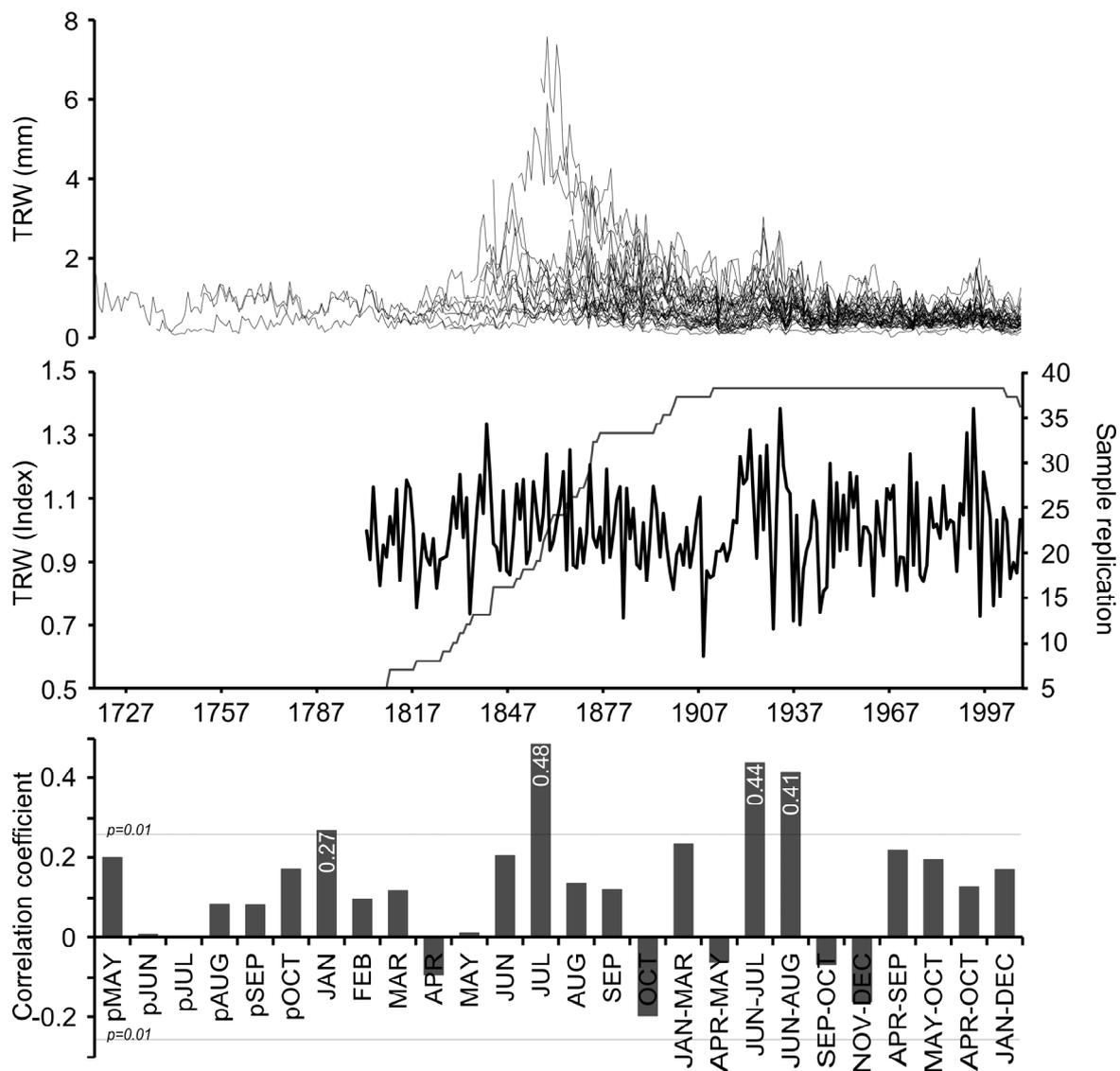
*Figure 3: Spaghetti plot for 38 tree-ring width measurements, the TRW residual chronology built using 38 TRW series and correlation coefficient results for TRW chronology.*

The climatic analysis performed using the new chronology combining a selection of 38 (better-correlating) trees revealed a stronger temperature signal for July (r = 0.48), June-July (r = 0.44) and June-August (r = 0.41). It demonstrates that the selection of trees with the highest correlation values helps improving the climate signal of the TRW chronology. The whole calculations for 122 individual tree-ring series against temperature and precipitation of 26 months and periods (6344 correlations) took 1180 milliseconds.

## Conclusions

DendroCorr helps in fast and easy calculation of the Pearson correlation between dendrochronological (chronologies and individual series) and climate data. Thanks to intuitive use and no learning curve program is user-friendly. At the same time, it is highly useful due to multiple file types support and ability to instantly provide results, which are also available in visual representation (plots).

## Acknowledgments

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# The influence of compression wood on the strength of the climatic signal in tree rings of Norway spruce

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## Introduction

Trees are able to develop special tissue, so-called *reaction wood,* in order to counteract mechanical stress caused by e.g. wind, unstable slope or snow load (Pillow & Luxford 1937, Timell 1986, Plomion et al. 2001). If tension and/or compression affect the tree, tension wood forms in angiosperms and compression wood (CW) in gymnosperms. CW forms on the lower side of inclined stems, mostly the side opposite to mechanical pressure (Timell 1986, Plomion et al. 2001), and its presence usually involves eccentric radial growth (e.g. Westing 1965, Plomion et al. 2001, Wistuba et al. 2013). The main role of CW is to push the leaning tree upwards to its vertical position (Scurfield 1973, Wilson & Archer 1977, Timell 1986, Zobel & van Buijtenen 1989, Plomion et al. 2001). Compression wood can vary in intensity and position within the tree rings and it can constitute the entire ring, whole or part of the latewood or some portion of the earlywood (Yumoto et al. 1983, Singh & Donaldson 1999). Typical severe compression wood is characterized by rounded and short tracheids, intercellular spaces, absence of a S3 layer, presence of helical cavities in the S2 layer and enhanced lignification (Pillow & Luxford 1937, Timell 1986, Ruelle 2014). In mild CW features such as cell wall thickness and circularity of cells are reduced compared to the severe CW (Yumoto at al. 1983, Donaldson et al. 1999, Singh & Donaldson 1999, Donaldson et al. 2004). Moreover, the color of the mild CW category is less intense than the severe form of CW (Timell 1986).

The occurrence of compression wood is widely used in dendrogeomorphological studies to reconstruct the frequency and intensity of mass movements such as debris flows (Gärtner & Stoffel 2002), landslides (Saez et al. 2012), avalanches (Corona et al. 2012), or floods (Ruiz-Villanueva et al. 2010). In dendroclimatology, however, CW rather constitutes an obstacle (Schweingruber 2007)*,* and samples containing severe, clearly visible CW are usually excluded from measurements of tree-ring width, wood density or stable isotope ratios. In fact it is often difficult to avoid the presence of any, even mild compression wood, particularly because many samples for dendroclimatological studies often originate from trees grown at mountainous slope sites. Standard sampling strategies recommend the sampling of tree cores on those positions of the stem perpendicular to the slope. In theory this routine should prevent collecting samples affected by compression wood, but still mild compression wood could easily pass the examination and be included in the analyses.

There is a lack of systematic investigations on the influence of compression wood on the climatic signal in any tree-ring parameters traditionally used in dendroclimatology. From our knowledge only Luckman & Kearney (1986) and Luckman & Gray (1990) investigated the influence of compression wood on tree-ring parameters, however, with a focus on oxygen isotope ratios ($\delta^{18}$O). Luckman & Kearney (1986) reported that the climatic signal in $\delta^{18}$O series of the CW radii of their study trees is as strong as in $\delta^{18}$O series of the side opposite to CW. However, tree rings containing CW had about 1.0‰ – 1.4‰ higher $\delta^{18}$O values than normal wood. Luckman & Grey (1990), however, claimed that compression wood could mask the climate signal in tree-ring $\delta^{18}$O. Although the results of both studies are innovatory, they also show certain limitations, such as lack

of reference samples, only one tree was used for the analysis, and limited representativeness of the climate data.

The overall aim of our study is to test if and how the presence of compression wood does affect the strength of the climatic signal in tree-ring width, blue reflectance, and stable carbon and oxygen isotope ratios ($\delta^{18}O$ and $\delta^{13}C$) in tree rings of Norway spruce. Since data processing and analysis is still underway, we here present first results from the tree-ring width (TRW) related part of the study only.

## Study area

Our study was conducted in the Kościeliska Valley (49°15'N 19°52'E) in the Western Tatra Mountains, Western Carpathians, Poland (Figure 1). The sampling site is located in the lower part of the Kościeliska Valley, built of sedimentary rocks, mainly limestone and dolomite (Bac-Moszaszwili et al. 1979). The sampling site is situated at around 1000 m a.s.l. on a slope with western exposition and 15° inclination. Forests in this region are dominated by Norway spruce (*Picea abies* L. Karst). Soils are mainly represented by haplic cambisols and brown regosols (Skiba 2002).

The climate of the Tatra Mts. is influenced by polar marine (65%) and polar continental (25%) air masses (Niedźwiedź et al. 2015) and local topography. The annual precipitation amount ranges from 1100 mm at the foothills (Zakopane, 844 m a.s.l.) to 1889 mm on the summit Kasprowy Wierch (1991 m a.s.l.). At an elevation of around 1000 m a.s.l. (Dolina Chochołowska) the annual precipitation reaches 1200 mm (Niedźwiedź 1992). The precipitation maximum is concentrated in summer (June-August). The mean annual temperature (1931-1960) at the elevation of the study site is about 3.6°C. Minimum and maximum temperatures are -32.1°C and 30°C, respectively. July and August are the warmest months with temperatures of 14.8°C and 13.8°C, respectively.
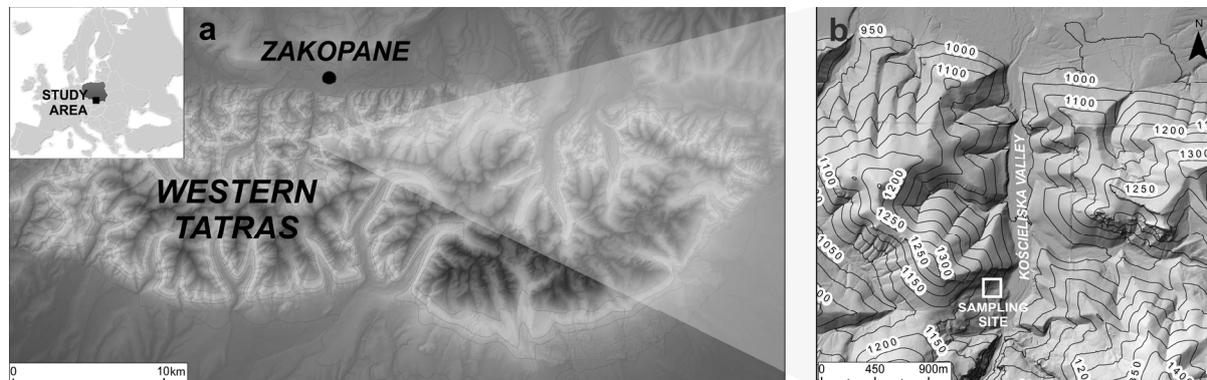


Figure 1: Location of the meteorological station Zakopane (black dot in a) and the study site (square in b).

## Material and methods

Our wood material originates from trees that were uprooted in December 2013 during a severe storm with wind speed up to 180 km/h. Discs from 12 Norway spruce trunks with obvious CW and eccentric growth were collected with a chainsaw. The main cause of compression wood formation in these trees was most probably slow mass movement (creeping) of the regolith. The sampled trees were around 100 years old and the collected discs were free of rot and visible growth disturbances such as scars or traumatic resin ducts.

All discs were sanded with abrasive paper (60 and 800 grid) and scanned with high image resolution (1200 DPI). For each of the twelve discs one radius with the strongest compression wood (downslope side of the trunks) was selected based on macroscopic features (red-brown color on wood surface, thickness of the latewood) (Fig. 2). Three additional radii were taken, one from the opposite side of CW and two perpendicular to the CW radius (Fig. 2).
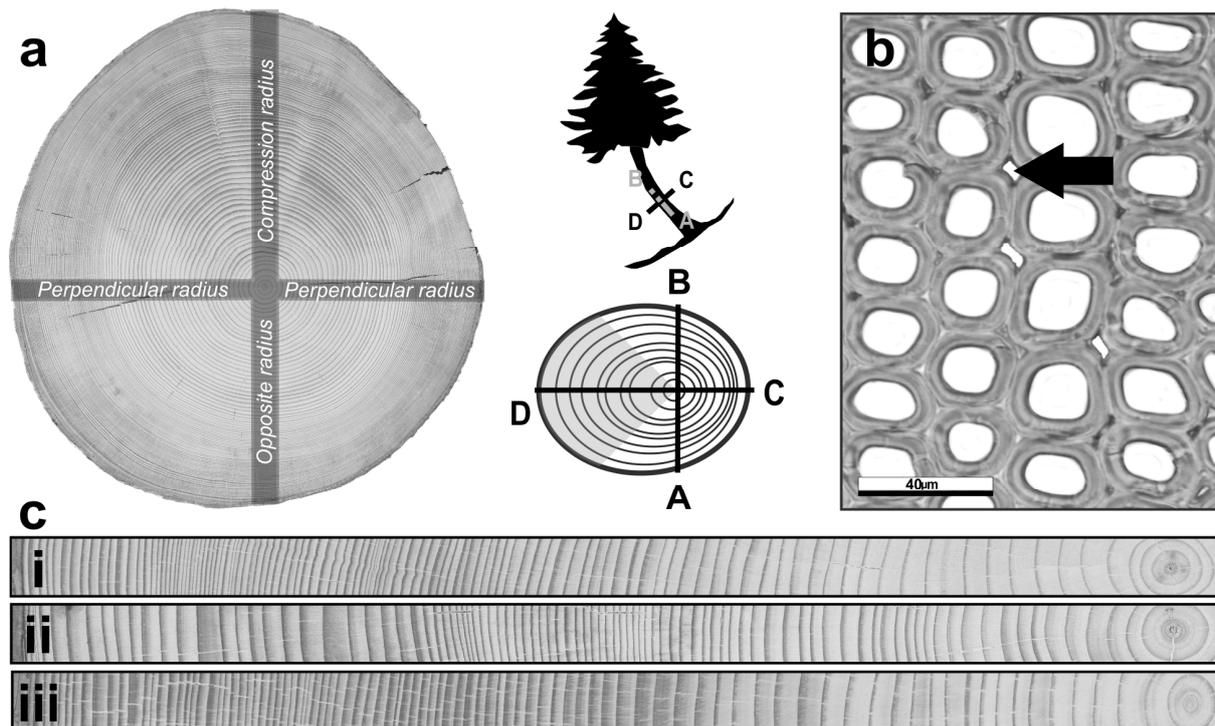
*Figure 2: Sampling design (a): perpendicular radii (A and B), opposite wood radius (C), compression wood radius (D); micro section with 40µm resolution showing the characteristic intercellular spaces (arrow) and rounded cells (b); and three examples of compression wood occurrence of different intensity (i = very mild, ii = mild, iii = strong) (c). All pictures are from Norway spruce trees of this study.*

TRW was measured on the images with the CooRecorder 8.0 software (Larsson 2013). The quality and synchronicity of the measurements were tested based on visual (CDendro) and statistical (Cofecha software, Holmes 1983) analyses.

Raw and 60-year spline detrended (*Arstan program version 44h3*; Cook 1985) chronologies were built for: i) CW radii ('chronology CW'), ii) the radii on the opposite site of CW ('chronology opposite'), iii) two radii perpendicular to CW ('chronology perpendicular'), and iv) all 4 radii ('chronology all'). Inter-series correlation (Rbar) (Cook & Kairiukstis 1990) and Expressed Population Signal (EPS) (Wigley et al. 1984, Briffa & Jones 1990) were computed in 30-year moving windows with 15 years lag to assess the internal coherence of tree-ring series and reliability of the chronologies.

The eccentricity indices (Iex) were calculated from raw TRW data of the down- and upslope sides of each single tree (Schweingruber 1996) (Fig. 3) as follows:

$$I_{ex} = \frac{\text{ring-width downslope}}{\text{ring-width upslope}}$$

The same formula was applied to calculate the quotient of two perpendicular radii. The eccentricity index can help to identify the timing and strength of growth changes generally related to compression wood.

For the analysis of climate/growth relationships, monthly data of mean air temperature and monthly precipitation sums were used from the nearest meteorological station Zakopane (860 m a.s.l.) (Fig. 1) located 7.8 km distance to the study site. For the quantification of the strength of the climatic signal Pearson's correlation coefficients were calculated between climatic data and each of the four detrended chronologies over the 1920-2000 period.

## Results and Discussion

Although TRWs of the compression wood radii are usually wider than those of the opposite side, time series from all radii exhibit similar high-frequency variation (Fig. 3). This is confirmed by the fact that r-values for the cross-correlations between individual radii are highly significant for each tree (*p<0.01*). In comparison the offsets between the two perpendicular radii are much smaller and both long-term trends and high-frequency variations are similar (Fig. 3).
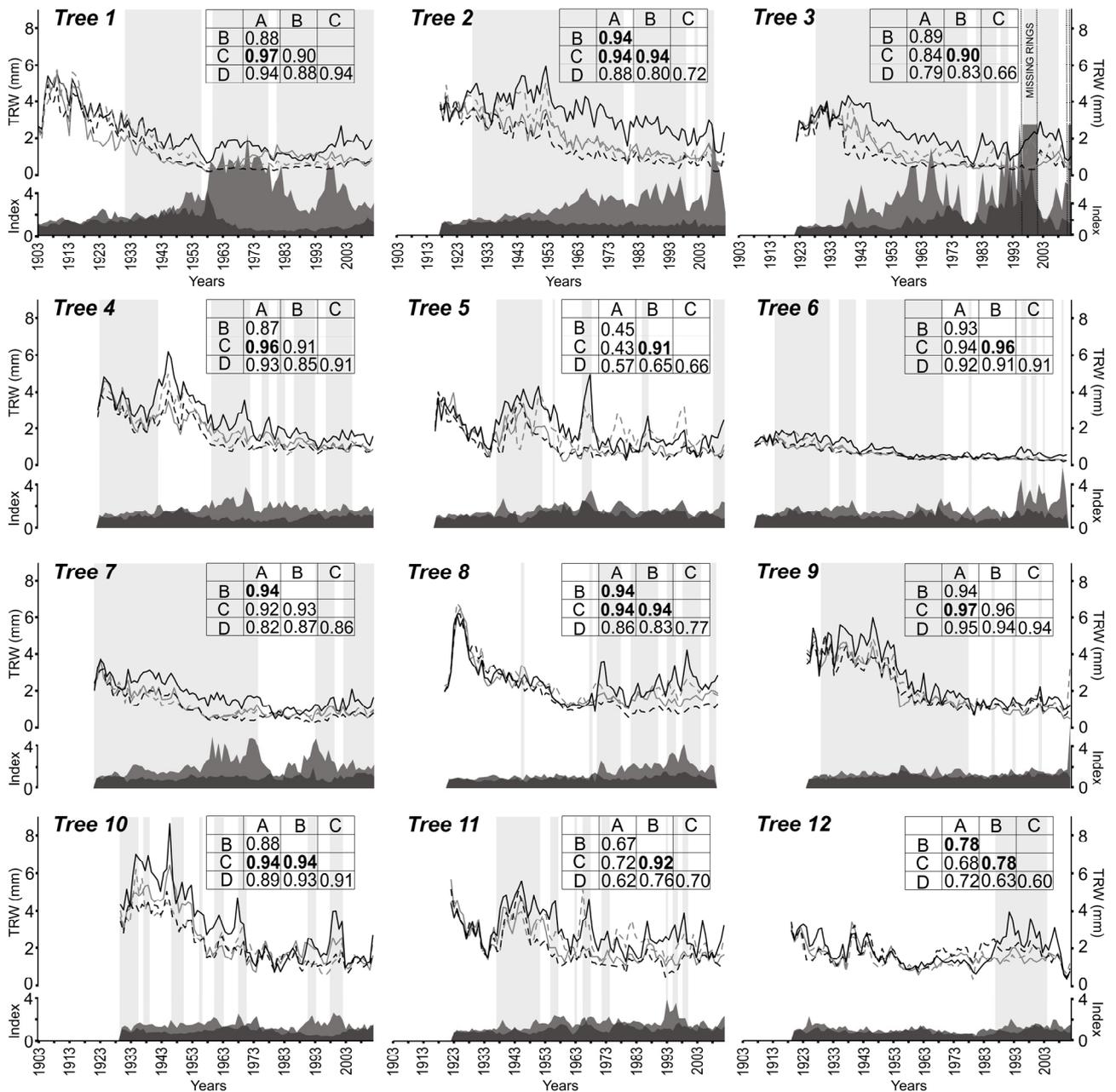


*Figure 3: Raw TRW data for 12 trees and 4 radii, and eccentricity indices (Iex). Black solid line = CW, black dotted line = opposite, grey solid line and grey dotted line = two perpendicular. The tables present the correlation coefficients between all individual radii for each tree: two perpendicular radii (A and B), opposite wood radius (C), and compression wood radius (D). Areas in the lower panels indicate the Iex for CW and opposite side (light grey) and two perpendicular radii (dark grey). Light grey areas covering both panels indicate the occurrence of CW.*

The onset and the duration of compression wood vary from tree to tree (Fig. 3). Only in four of twelve investigated trees compression wood started in the same years (1981, 1993, 2002). The number of tree rings with CW differs also between trees. In six trees the duration of compression wood occurrence is extended to 40 years while the average duration equals 10 years. The macroscopically identified anatomical features of the compression wood change from rings fully constituted by CW through only the latewood cells showing the characteristics of CW to the intra-annual wood density fluctuations within earlywood.

The periods of mild compression wood presence are not fully synchronized with the periods of high eccentricity index values (Fig. 3). The comparison between CW and opposite radii revealed that in 67% of the studied trees the occurrence of compression wood coincides with the eccentricity of the tree rings.

All studied trees revealed generally wider rings at the downslope side of the trunk rather than at the opposite side but with several exceptions. These exceptions concern the first years of juvenile wood (15 years) with only mild CW, when the pattern of growth is similar between CW and the opposite radii for 67% of our studied trees. Moreover, in 1980 50% of our trees produced a very narrow ring with almost identical width at both sides of the stem. None of the trees exhibited the occurrence of compression wood in this year. The very narrow ring in 1980 can be related to unfavorable climatic conditions, i.e. low temperatures at the beginning of the growing season hampering the start of cambial activity and photosynthesis. The mean temperatures in May and June in 1980 were by 3.4°C and 1°C, respectively, lower than the long-term mean for the same months with respect to 1901-2000 (Zakopane).

Taking the raw measurements of all 12 trees into account, the maximum values of TRW of CW radii range from 1.95 to 8.65 mm and the narrowest from 0.23 to 1.23 mm, whereas the mean value varies between 0.82-3.38 mm. For the upslope radii, the widest, mean and narrowest rings are in a range of 1.67-5.92 mm, 0.52-2.22 mm and 0-0.84 mm, respectively. Furthermore, at the upslope radius of tree number 3, five missing rings were detected. For both perpendicular radii the maximum, minimum and mean values are in a range between 1.57-6.5, 0.06-0.98, and 0.53-2.39 mm, respectively.

In general in all raw chronologies the high and low frequency patterns are similar (Fig. 4). Although the values of the raw CW chronology are higher than for the others, the ring width values in the period 1917-1933 and in 1980 (both discussed previously) are almost identical for all chronologies. The similarities between four chronologies increase when detrended values are compared. The detailed parameters of established chronologies are presented in table 1.
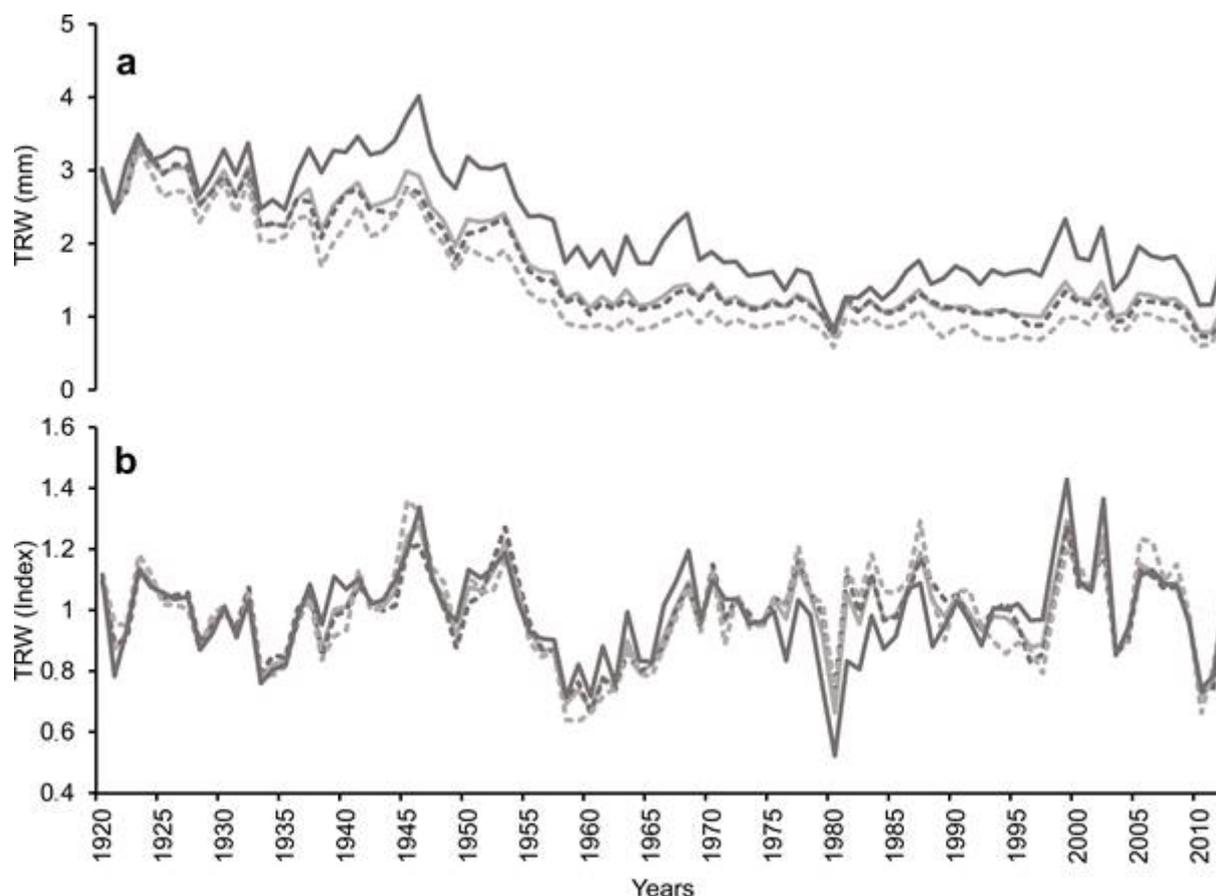
*Figure 4: The 4 raw (a) and 4 60-year spline detrended (b) chronologies, cut at a replication <5 trees. Dark grey solid line = CW, light grey dotted line = opposite radii, dark grey dotted line = two perpendicular radii, and light grey solid line = four radii.*

*Table 1: Characteristics of the four 60-year spline detrended (STD) and raw chronologies (RAW). EPS (expressed population signal) and Rbar (inter-series correlation) calculated for both chronologies and MSL (mean segment length, in years), MGR (mean growth rate, mm/year) for the raw chronology.*

| Chronology | No. of series | Length | MSL | MGR | Rbar | | EPS | |
|---|---|---|---|---|---|---|---|---|
| | | | | | RAW | STD | RAW | STD |
| CW | 12 | 1920-2012 | 94 | 2.23 | 0.38 | 0.35 | 0.84 | 0.86 |
| Opposite | 12 | 1920-2012 | 94 | 1.44 | 0.41 | 0.34 | 0.85 | 0.84 |
| Perpendicular | 24 | 1920-2012 | 94 | 1.68 | 0.49 | 0.40 | 0.92 | 0.92 |
| All | 48 | 1920-2012 | 94 | 1.74 | 0.47 | 0.40 | 0.96 | 0.96 |

All four standard chronologies correlate positively and significant (*p<0.01*) with temperature whereas no significant correlation with precipitation was found at all (Fig. 5). Ring development at our site seems to register a temperature signal over the full growing season from April to September, indicated by the highest correlation to this period of all chronologies. A temperature signal in Norway spruce from the same elevation has also been reported from other parts of the Tatra Mountains (Savva et al. 2006, Büntgen et al. 2007, Czajka & Kaczka 2011) although in all of these studies the signal was more restricted to June-July. Several reasons could account for this, including differences in local site conditions, in replication of the chronologies, or, most interestingly, a potential alteration of the climatic signal in compression wood (see below).

As expected, the strength of the temperature signal varies depending on which radii are considered. Contrary to our presumptions the signal contained in the CW chronology for the entire

growing season is not weakened, but is even strongest (r=0.46), and clearly exceeds the signal strength in the chronology of the two perpendicular radii (r=0.34), representing those normally used in dendroclimatology. Although the perpendicular chronology is built with 24 radii (2 radii per tree) and therefore exhibits higher EPS and Rbar, the climatic signal is still weaker than in the CW chronology.

However there is an important difference on a monthly basis. Whereas the perpendicular chronology shows the strongest (although not significant) correlation to temperature in September, the CW chronology shows a significant correlation to April temperature. The weakest (although still significant) signal contains the chronology of the radii opposite to CW (upslope radii). Similarly high correlation values for temperature and CW have been reported by Esper et al. (2008) for *Pinus cembra L.* of different age in the Swiss Engadin in the central European Alps.
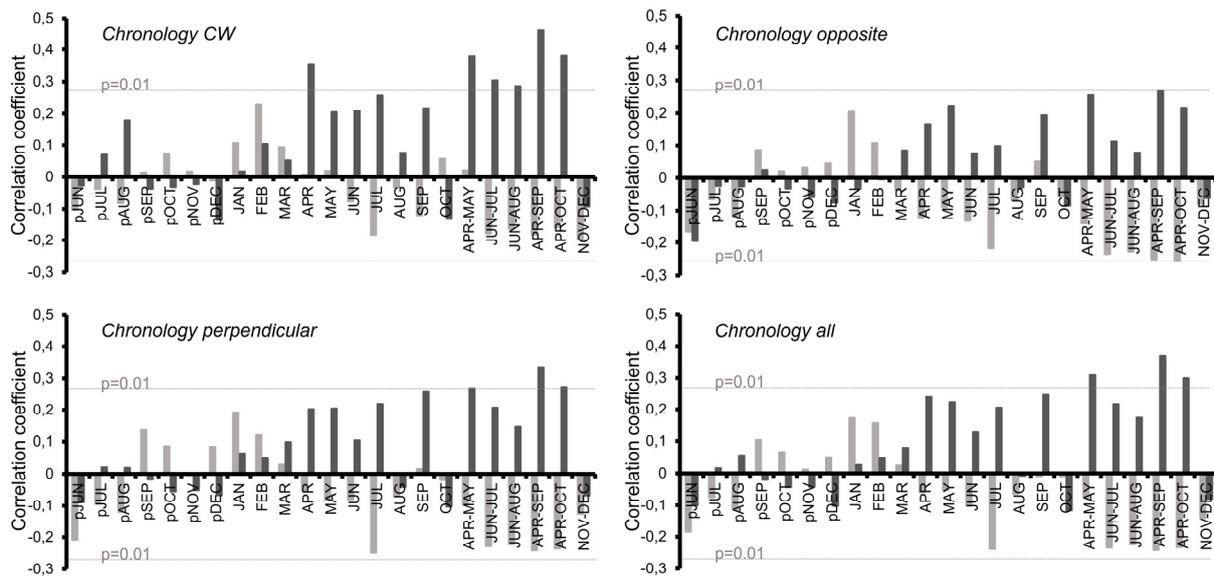


*Figure 5: Pearson's correlation coefficients calculated between the four standard chronologies and temperature (dark grey) and precipitation (light grey) from previous June to October of the current year, and different combinations of months.*

The studied tree rings in the CW radii are generally wider than those at the opposite side of the trees, because of the greater number of cells as well as thicker cell walls. The production of wider tree rings formed at the compressed side of the stem requires more resources, i.e. carbohydrates (Timell 1986). As a consequence, less carbon is fixed at the opposite side (Timell 1986), resulting in narrower rings. Although there is still little known about the mechanistic processes of CW xylogenesis, it is assumed that the cambium acts at a faster rate and the period of xylogenesis is longer (Palombo 2013). It was shown with *Pinus mugo* above the timberline of the Central Apennines/Italy that differentiation and lignification of CW cells lasted around two weeks longer (10%) than at the opposite side (Palombo 2013). Although the latter process does not influence the ring width, it is important in terms of cell wall thickness, which is one of the key characteristics of compression wood. We could expect similar differences in xylogenesis of CW cells and xylem cells at the opposite side of the stem in Norway spruce. Therefore, the longer period of tree-ring formation might integrate the climatic conditions over more months during the growing season with increased importance of spring (April) and autumn (September) temperatures.

## Conclusions

Our findings tend to question the common assumption that climatic signals in TRW chronologies might be weakened by the presence of compression wood. Although we here present preliminary

results only, they could already be of high relevance for future sampling strategies for dendroclimatological studies. Taking tree cores from the CW part of the stem normally strictly excluded from any sampling, could rather improve than weaken the strength of the climatic signal for the entire growing season in TRW. Collecting samples from the perpendicular side of the stem does not ensure that the climate/growth relationship is maximized, and samples taken at the opposite side of CW seem to contain the weakest climatic information. The preliminary results suggest not diminishing but rather altering such signal (from June-July to April-September temperatures). However, the difference revealed for the monthly correlation indicates a different physiological effect. Potentially compression wood needs more favorable conditions at the beginning of the growing season than the other structures to build up dense xylem. For sure this needs to be tested with more strongly replicated data sets, for samples including severe compression wood, and other tree species and sites, which are rather sensitive to drought than to temperature. Moreover, we still need to better verify our hypothesis, that the presence of compression wood leads to a climatic signal integrated over a longer period during the growth season compared to non-compression wood. We are, however, already convinced that in cases where one would need to switch for some reasons from the perpendicular side to another side of the stem during sampling, the downslope part should be preferred compared to the upslope part. Follow-up work is already on-going to test, how far our results also hold for other tree-ring parameters such as Blue Reflectance and stable isotope ratios. Moreover we will test the robustness of our results with higher replicated data sets.

## Acknowledgement

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# Evaluating climate sensitivity in tree-ring and Riesling must sugar data from the Palatinate (Germany)

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## Introduction

The Palatinate Forest, a low mountain range in southwest Germany, represents the largest contiguous forested area of the country. This region is characterized by pronounced dry conditions due to thes and stone bedrock and associated sandy soils. Its north-south orientation and associated lee-effects, due to predominating westerlies together with altitudinal differences of more than 300 m, lead to high temperature means and low precipitation totals. Here, the forest comprises a proportion of up to 80 % of pine trees, a result of historical management activities (personal communication with the forester of the area). The vegetation outside the forested areas in the plain is characterized as agricultural croplands with vineyards, representing one of the largest wine-growing regions in Germany.

Although viticultural data, i.e. grape harvest dates and grapevine yields, can serve as temperature proxies (Pfister 1981, Chuine et al. 2004, Duchêne et al. 2010, Urhausen et al. 2011b, Urhausen et al. 2011a) this relationship has not been assessed in this specific region. In the low mountain ranges, ring width increment from conifers is typically not solely controlled by one single climate parameter(Hartl-Meier et al. 2014). Analyzing must (grape juice) sugar content data might elucidate our understanding of longer-term climate variability in the Palatinate region, since temperature-sensitive must sugar content data has been reported from other regions in Germany (Urhausen et al. 2011b, Bock et al. 2013).

Here, we present tree-ring width of 487 *Pinus sylvestris* core samples and correlate these against regional meteorological station (1950-2012) and gridded data (1891-2010/12). In addition, we utilize a dataset of 30 consecutive years (1984-2003) of Riesling must sugar content from three vineyards adjoining the forested area into the plain.

## Material and methods

### Sampling sites and data treatment

For tree-ring width (TRW) measurements, we selected seven sites at the eastern ridge of the Palatinate Forest and sampled503 cores of *Pinus sylvestris* trees at ~500-600 m asl (mostly two cores per tree), ranging between 43 to 148 cores per site and spanning the period 1841-2012 at a minimum replication of 10 cores (Fig. 1).TRW was measured, absolutely dated and verified using a LinTab/TSAP device (Rinn 2007) and the COFECHA program (Holmes 1983). Several detrending techniques were applied using the ARSTAN software to remove non-climatic trends linked to juvenile growth fluctuations (Fritts 1976, Cook 1985). We applied 10-year cubic smoothing splines (TRW$_{10spline}$)(Cook & Peters 1981), negative exponential functions (Fritts 1976), and Regional Curve Standardization (TRW$_{RCS}$)(Esper et al. 2003) to compute dimensionless indices highlighting climatic information in varying frequency domains. All data were power-transformed prior to detrending(Cook & Peters 1997). Index chronologies were calculated using robust bi-weight means, while variance was stabilized pondering varying replication and interseries correlations (rbar) (Frank et al. 2007). Rbar and Expressed Population Signal (EPS) were calculated using 31-year moving windows with 30-year overlap (Wigley et al. 1984) (Fig. 2). Specific site characteristics

enabled re-organisation of the dataset into samples originating from trees growing in more steep (slope) and flat (plateau) situations spanning the period 1841-2012 and 1869-2012, respectively.

Must sugar is usually measured in degrees Oechsle (°Oe), which relates the density of must to pure water. We calculated a mean chronology using data originating from three nearby Riesling vineyards adjoining the forested area in the plain (Fig. 1). The data were provided by a local winegrower and span the period 1983-2013 at annual resolution (Fig. 5).
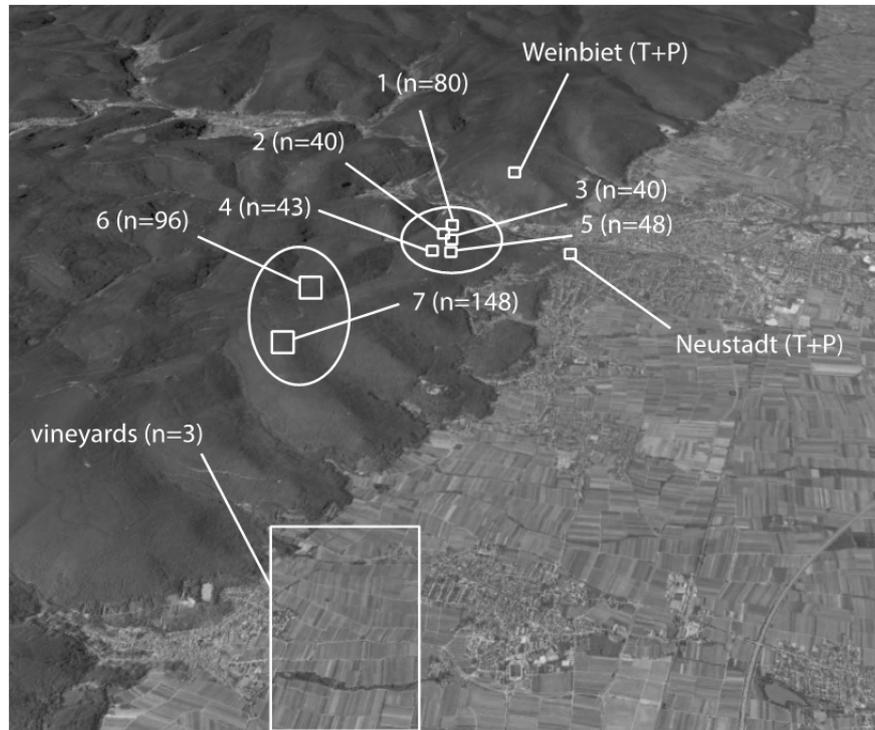


*Figure 1: TRW sampling sites (1-7, n=number of individual cores), vineyards(n=number of datasets) and meteorological stations in Weinbiet and Neustadt (T=temperature, P=precipitation).*

*Meteorological data and calibration efforts*

Temperature and precipitation measurements from two nearby meteorological stations, Weinbiet (49.38N, 8.12E; 553 m asl, 1953-2012) and Neustadt (49.35N, 8.14E; 146 m asl, 1950-1982), were used for calibration (Fig. 1). Due to the fragmented structure of both datasets (Weinbiet: seven years missing; Neustadt: eleven years missing), we calculated anomalies with respect to the longest consecutive period in both datasets (1954-1974) and filled the gaps of the Weinbiet-datasets with anomalies from the Neustadt station. In addition, gridded data were used to verify the combined datasets and to assess the influence of two versions of the self-calibrating Palmer Drought Severity Index (scPDSI): (1) UCAR scPDSI (University Corporation for Atmospheric Research: Dai et al. 2004, Dai 2011) and (2) CRU scPDSI (Climate Research Unit: van der Schrier et al. 2006). Data were collected from the nearest grid-points at 48.75N/49.25N and 8.75E/8.25E, respectively.

Both the TRW and must sugar data were correlated against monthly instrumental data over the 1950-2012 period, while gridded data enabled the application of longer calibration periods from 1891-2010/12, thereby supporting an assessment of the temporal robustness using split calibration approaches. By high- and low-pass filtering all data, using 15- and 31-year cubic splines and residuals thereof, the frequency-dependent coherency between the proxy- and target data was estimated (Fig. 5). We used the KNMI Climate Explorer for spatial correlations of must sugar data against gridded April-August temperatures over the 1950-2012 period, using the E-OBS dataset

(EU-FP6 project ENSEMBLES and ECA&D project: Haylock et al. 2008), due to a higher spatial resolution.

## Results and discussion

### TRW data and growth-climate relationships

Our newly produced TRW dataset from the Palatinate Forest spans the period 1832-2012 and with good replication (≥10 radii) back to 1841 (Fig. 2).Although growth of *Pinus sylvestris* trees in low mountain ranges is often weakly related to a single climatic factor, interseries correlation ($rbar_{mean}$=0.57) and EPS values denote a high and temporally robust coherency among the samples (see bottom panel in Fig. 2).
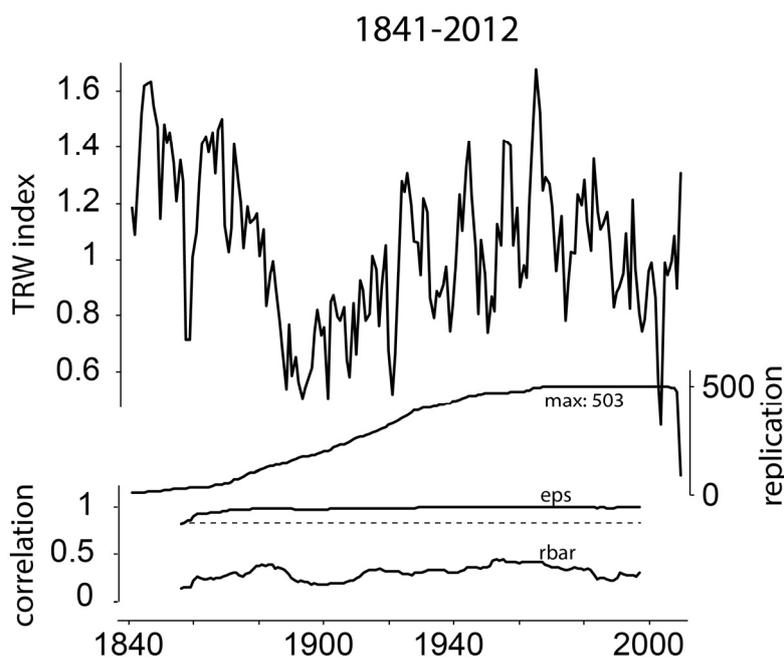


*Figure 2: RCS detrended chronology, replication, and running rbar and EPS statistics.*

Growth-climate response trials reveal mixed signals, including significant correlations with seasonal temperature, precipitation and drought indices (Fig. 3). $TRW_{RCS}$ at the slope sites shows strongest negative relationships with April-June temperatures ($r_{1950-2012}$=-0.44, p<0.01), whereas$TRW_{10spline}$ from the plateau sites reveals highest correlations with June-July precipitation ($r_{1950-2012}$=0.31, p<0.05) (fig. 3, left panels).At the slope sites, tree growth is reduced with higher temperatures, likely because exposition increases the maximum angel of insolation, together with increased surface water run-off limiting trees' water availability. Using all $TRW_{RCS}$ data, only a significant April-June temperature signal can be obtained ($r_{1950-2012}$=-0.33, p<0.05). A clearer pattern is found when correlating $TRW_{RCS}$ data with scPDSI (Fig. 3, right panels). All monthly correlations are positive with the highest value obtained for $TRW_{RCS}$ from the slope sites against the seasonal mean of April-August ($r_{UCAR1950-2010}$=0.50, p<0.001) or April-June ($r_{CRU1950-2012}$=0.47, p<0.01). Additionally, $TRW_{RCS}$ from plateau sites exhibits significant correlations ($r_{UCAR1950-2010}$=0.41, p<0.01; $r_{CRU1950-2012}$=0.35, p<0.05).

To explain tree growth at all sites, using only temperature and precipitation data is not satisfying. The growth-climate relationship at the Palatinate Forest may be best estimated by drought-related indices, since these data integrate temperature, precipitation, and soil information. Due to the unique ecological setting in the area, soil information and water availability seem to be key to tree growth over the 1950-2010/12 period.

Temperature (1950 - 2012)

UCAR scPDSI (1950 - 2010)



Precipitation (1950 - 2012)
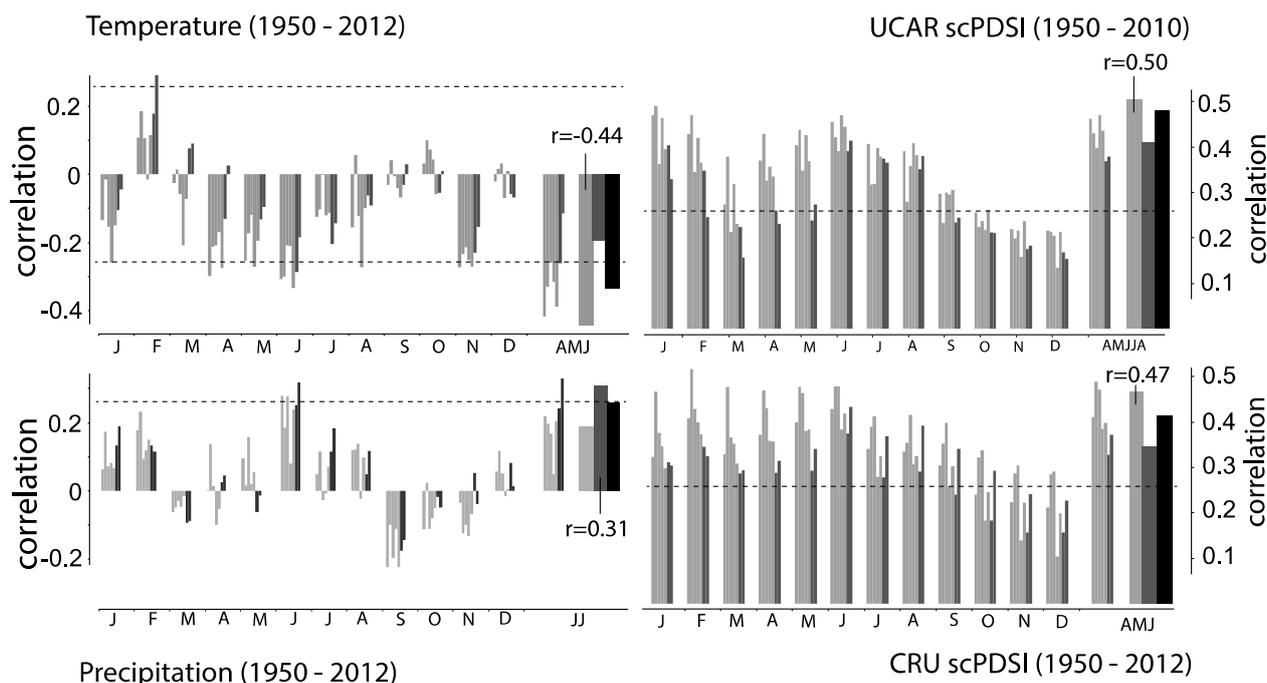
CRU scPDSI (1950 - 2012)

*Figure 3: Growth-climate relationship expressed as correlations between TRW and instrumental climate data. Upper left: correlations with temperature data (TRW: RCS detrended); lower left: correlations with precipitation data (TRW: 10-year spline detrended); upper right: gridded UCAR scPDSIdata (TRW: RCS detrended); lower right: gridded CRU scPDSI data (TRW: RCS detrended).Dashed lines indicate significance levels (p<0.05). Lighter grey indicates the five slope-sites, dark grey the two plateau-sites, and black all data.*

The significant relationship between TRW from the slope sites and April-August scPDSI over the 1950-2010 period is not restricted to more low-frequency trends ($r_{LP}$=0.88), but also found in the high-frequency year-to-year variations ($r_{HP}$=0.32) (Fig. 4).However, extending the calibration period over the full 20th century reveals a temporal shift of the growth-climate relationship. Comparison with UCAR scPDSI over the full period1891-2010 unfolds insignificant results ($r_{1891-2010}$=0.15), particularly in the early period 1891-1949 the drought signal appears to be absent (r=-0.05). This temporal shift either indicates that the climate control of tree growth varied over the 20th century, or that the early instrumental climate data are biased by larger uncertainties(Wijngaard et al. 2003).
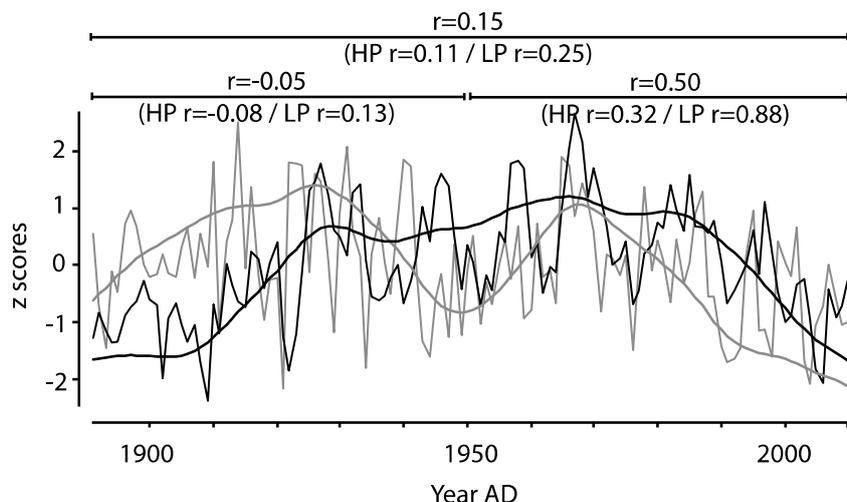


*Figure 4: Slope sites TRW chronology (black) and Apr-Aug UCAR scPDSI (grey), original and smoothed (31-year cubic spline) data. r = correlation values, LP = low-pass filtered data using 31-year cubic smoothing splines, HP = high-pass filtered data using residuals from the splines.*

*Must sugar data and sugar-climate relationships*

The must sugar and summer temperature data synchronize very well (Fig. 5). Monthly calibration results exhibit a distinct pattern of positive correlations throughout the vegetation period, except from October, the month of the grape harvest (Fig. 5, upper right panel). For the best responding season April-August, significant correlations can be observed ($r_{1983-2013}$=0.67) over the full 1983-2013 calibration period, while growth-climate relationships between TRW from the slope sites and April-August scPDSI appear weaker in comparison ($r_{1983-2010}$=0.39). High-pass filtering the data underlines the stronger coherency between the must sugar and temperature ($r_{1983-2013}$=0.49), thereby verifying a distinct association not only in the low-frequency domain but also in the year-to-year variations. Results of a split calibration approach with two equidistant periods indicate no temporal shift or signal losses in both, original and high-pass filtered data.
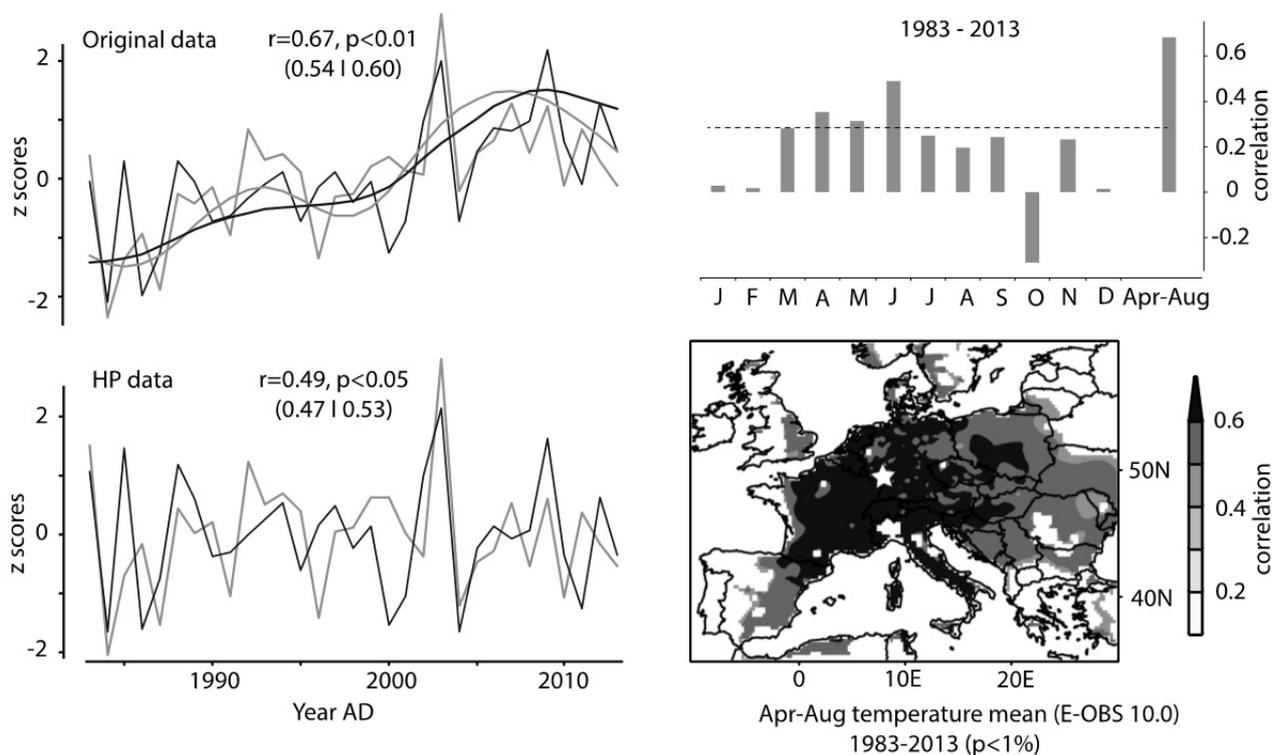


*Figure 5: Climate sensitivity of must sugar data. Upper left: Original and smoothed (11-year cubic smoothing spline) must sugar data (black) and Apr-Aug temperature data (grey), with r = correlation values, p = significance level. Numbers in brackets indicate correlation values from split calibration. Lower left panel shows the 11-year high-pass filtered must sugar and temperature data. Upper right shows the monthly and seasonal sugar-climate correlations, with the dashed line indicating significance p<0.05. Lower right shows the European correlation field of the original must sugar data against gridded E-OBS data (p<0.01).*

The analysis of sugar-climate relationships over space reveals a widespread representativeness of the data (Fig.5, lower right panel). Areas with correlation values of r>0.6 almost completely cover Central Europe, Italy and parts of Eastern Europe. The changing climate envelope as a function of time plays an important role in the assessment of climate-induced changes in plant phenology and ecology (Chuine et al. 2000), including trees and grape vines (Chuine et al. 2004, Jones et al. 2005, Hartl-Meier et al. 2014). Our findings indicate that must sugar data from the Palatinate could contribute to paleoclimatic research in Europe when developing datasets in centennial timescales. The relationship of sugar content in grapes and temperature is well known among wine growers (Pfister 1981, Urhausen et al. 2011a, Bock et al. 2013), but has not been used in a European paleoclimatic perspective. The impact of modified seed, genetic technology, and cultivation methods, particularly in the 20th century requires further assessments and research (Duchêne et al. 2010, Bock et al. 2013).

## Conclusions

Although the low mountain range of the Palatinate Forest offers at its most eastern transition zone to the Upper Rhine Plain a unique climatological and ecological setting, a distinct growth-climate coherency in *Pinus sylvestris* trees is not detectable. Calibrating TRW data against regional temperature, precipitation and drought indices (scPDSI) reveals a mixed influence on growth, limiting TRW for paleoclimatic reconstruction purposes.

Must sugar data exhibit a clear coherency to temperature variations and may, therefore, contribute to potential summer temperature reconstructions for the Palatinate region in Germany. The temperature control in regional must sugar content is not limited to year-to-year variations, but seems also coherent in the lower frequency domain, though the 1983-2012 calibration period is too short to conclude on this issue. Extending the calibration period to cover the complete 20th century would be essential and improve the analysis of this relationship. Since TRW of conifers here and in other low mountain ranges in Central Europe is not fulfilling requirements for reliable paleoclimatic research, must sugar data may, in the long-term, contribute to the understanding of past climatic variations.

## Acknowledgements

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# Volcanic induced cooling in instrumental and tree-ring density data

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## Introduction

Deciphering the impact of large volcanic eruptions on large-scale climate can yield valuable information on climate sensitivity to radiative perturbations at short timescales (Masson-Delmotte et al. 2013). However, during the era of instrumental climate observations spanning roughly the past 150 years, the number of volcanic events is relatively small, and polar icecores indicate that the amount of radiation-absorbing sulphate injected into the stratosphere was much larger for several eruptions occurring earlier in the last millennium (Gao et al. 2008, Crowley & Unterman 2013). Analysis of climate archives with high temporal resolution, such as tree-rings, can increase the number of detected events and elucidate the full range of possible volcanic impact. Additionally, the large spatial distribution of tree-ring data provides a wide-angle perspective on climate variability that can dampen local anomalies and amplify externally driven climate variability. Thus, a large-scale tree-ring composite can be an appropriate tool for assessing volcanic feedbacks in the climate system.

A good understanding of the relevant proxy/climate-relationship is a prerequisite for analyzing volcanic-induced cooling using proxy reconstructions. Although temperature sensitivity is well established for tree-rings from high latitudes and altitudes (Fritts 1976), and although it is known that especially tree-ring density data are suitable for studying abrupt temperature changes(Esper et al. 2013, 2015), there are a few pitfalls associated with calculatingcooling estimates for volcanic events from tree-ring records:

(i)  Usually a linear relationship between temperature and tree-growth is assumed. This can be altered, especially in the case of volcanic events, by the influence of light availability (Robock 2005, Tingley et al. 2014).

(ii)  The network of proxy sites can be biased towards regions with weakeror stronger influence of volcanic activity or response to volcanic forcing. While this is a general problem of relatively sparse proxynetworks, it is of particular importance for the evaluationof a climate forcing usingpoint-source data.

(iii)  Aggregating or averaging spatial data might reduce the observed amplitude of volcanic cooling.

The hypotheses on light availability referenced in *(i)* are based on large-scale experiments. On local scales, proxy-derived temperatures were found to be in good agreement with long instrumental records (Esper et al. 2013), so that it seems likely that the integration of data over larger regions causes the offset observed in large-scale studies (Tingley et al. 2014). Here we address such potential effects by analyzing a hemispheric composite of maximum latewood density (MXD) chronologies. A summer-temperature reconstruction based on these data reflects distinct cooling in response to the largest eruptions of the last millennium (Schneider et al. 2015). By comparing this dataset with observational data from the 19th and 20th centuries, we intend to test its susceptibility to *(ii)* and *(iii)*, and to verify the cooling estimates derived from this record. We find that spatial aggregation yields systematic underestimation of volcanic induced cooling despite a reasonable hemispheric coverage of the MXDsites.

**Data and methods**

The proxy network represents all available MXDchronologies longer than 600 years from the Northern Hemisphere (NH). Data were processed using Regional Curve Standardization (Esper et al. 2003) and scaled (Esper et al. 2005) to local grid-point temperatures in order to derive local temperature reconstructions. The NH average is a 'composite-plus-scaling' (CPS) reconstruction (Von Storch et al. 2006) of extratropical (30-90°N) land-temperatures during the summer months June-August. For details see Schneider et al. (2015).

The instrumental target is the CRUTEM4v-dataset (Jones et al. 2012) with the same spatial (30-90°N, landmass) and seasonal (June-August) coverage. The gridded data reach back to 1850 for many parts of Europe and central North America, but temperature readings do not start before the late 19$^{th}$ or early 20$^{th}$ century for most grid points. In order to provide homogeneous spatial coverage, the NH-mean was calculated after applying a gapfilling procedure via the regularized expectation maximization algorithm using ridge regression (Schneider 2001). At the local scale, this method can introduce significant variance changes at gridpoints with large uncertainty ranges for the infilled data portion. This biasapplied to six sites within the network of 15 sites (see Fig. 1 c and f). Abruptly declining variance in the early portion of these records was adjusted to the level of the late 20$^{th}$ century in order to allow reasonable comparisons on a site-by-site level.

Past climate forcing of volcanic eruptions is usually based on sulphate deposition from multiple ice cores (Masson-Delmotte et al. 2013). Here, proxy and observational data were analyzed for volcanic signals considering the latest global ice core record (Crowley & Unterman 2013). It comprises a reconstruction of stratospheric sulphate expressed in aerosol optical depth (AOD) estimates. We include the volcanic events exceeding an AOD of 0.03 since 1874. Prior to that year the network of observational data is very sparse and the amount of grid points with data available is below 25%. The analysis period ends in 1976 representing the last year of the oldest (i.e. first developed) MXDchronology. Accordingly we included 1883 (Krakatau, Indonesia), 1902 (Santa Maria, Guatemala), 1912 (Novarupta, Alaska) and 1963 (Agung, Indonesia) with peaking AODvalues in 1884, 1903, 1912 and 1964. The temporal lag for tropical eruptions is caused by the delayed dispersion of the ash-column towards higher latitudes. Since AODvalues remain at an elevated level for at least one more year, we also consider this subsequent year. Temperature anomalies in response to volcanic activity were calculated with respect to the 5 pre-eruption years and averaged over the four eruptions.

In order to illustrate how the volcanic signal in proxy reconstructions can be affected by data processing, NH temperatures were reconstructed using the observations from the 15 grid boxes closest to the proxysites. This pseudo-reconstruction, free of proxyinduced noise, was rebuilt a 1000 times using alternative proxy networks, each consisting of 5 randomly chosen input records per continent (North America, Europe and Asia).

**Results**

Averaging summer temperatures during years of peaking stratospheric sulphate injection yields widespread cooling in the NH with a mean of 0.35°C below the 5 pre-eruption years (Fig. 1a and e). Central North America, southern Europe, western and eastern Asia are key cooling regions, whereas northwestern North America, eastern Europe and central Asia either show no significant coolingor they warm slightly. This pattern is replicated by the proxy records with an outstanding cooling response in northwestern Asia. Local gridpoint temperatures suggest a very similar cooling magnitude in line with the proxy data, and although the response in observational data is on average slightly lower, there is no clear evidence for a general over- or underestimation (Fig. 1c and e).
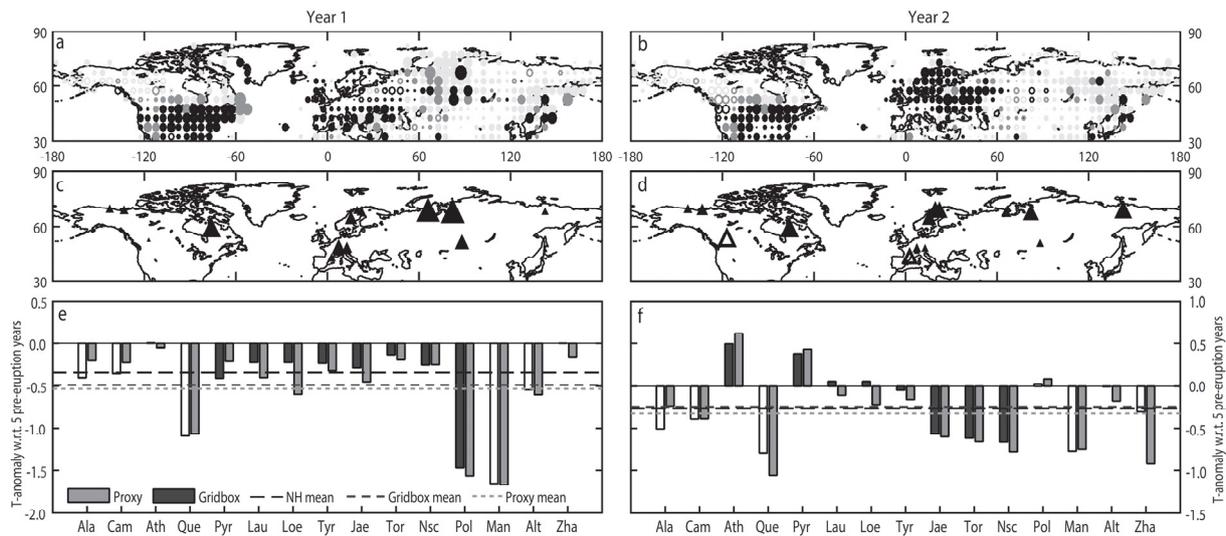
*Figure 1: Summer temperature cooling in response to volcanic eruptions in 1884, 1903, 1912 and 1964. (a) Anomalies of gridded summer temperature in years with peaking AOD with respect to the 5 pre-eruption years. Strongest cooling (warming) is indicated with the biggest filled (unfilled) dots. The greyscale represents the number of events covered by a gridbox before gap filling (light grey: 1964, medium grey: 1903, 1912, 1964, dark grey: 1884, 1903, 1912, 1964). (b) As in (a), but for the subsequent year. (c) MXD-sites used for the NH-reconstruction. Lowest (highest) MXD-values in the years with peaking AOD are indicated with the biggest filled (unfilled) triangles. (d) As in (c), but for the subsequent year. (e) Summer temperature anomalies for the 15 MXD sites in years with peaking AOD derived from proxy reconstructions and the gridded temperature field. Unfilled bars indicate gridboxes with short temperature records. A gap filling and variance stabilization were applied. (f) As in (e), but for the subsequent year.*

The second year after the sulphate spike is still dominated by cool conditions (-0.25°C on average), but with a clear shift of the key cooling regions (Fig. 1b). The most obvious change is found over Europe, where significant cooling affects the central and northern regions, while southern Europe and western Asia already display warming anomalies. The proxy records again agree with this pattern, and in keeping with the reduced overall cooling, there is more heterogeneity in the local responses: While some sites show even stronger coolingcompared to the first post-volcanic year, others exhibit warming relative to the 5 pre-eruption years (Fig. 1d and f). Averaging the 15 local estimates results in a somewhat stronger cooling than the average of the spatial field over the whole hemisphere. In the first post-volcanic year, reconstructed and observed temperatures are well below the overall average, whereas in the second year only the reconstructed anomalies suggest a slight overestimation (Fig. 1e and f).
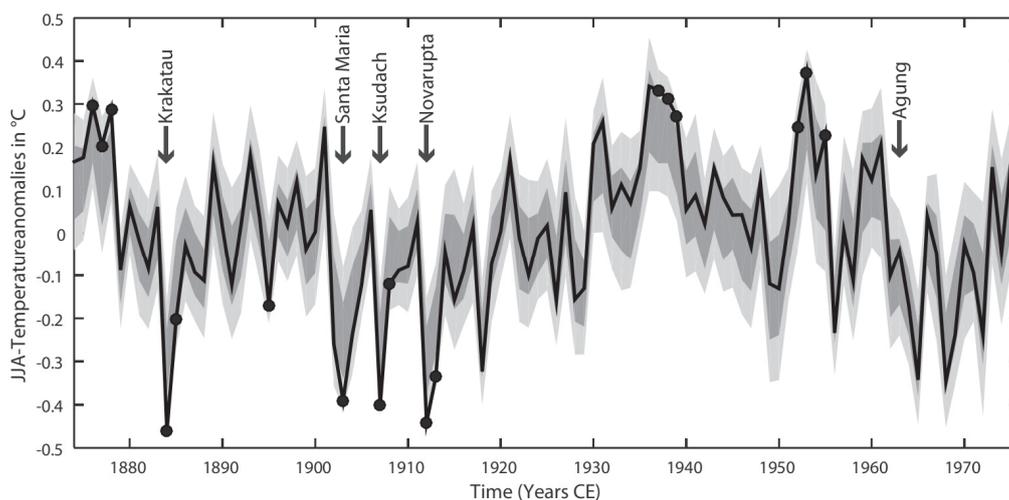
*Figure 2 | Summer temperature derived from the average of all grid points (black line) and from 1000 pseudo reconstructions (dark grey: 25th-75th percentile, light grey 10th and 90th percentile). Black dots indicate years in which the NH average exceeds the 25-75 percentile range. Arrows indicate selected volcanic eruptions.*

For large-scale examinations, proxy chronologies are compiled into one record, which is then scaled to the NH mean temperature (CPS reconstruction). The NH reconstruction based on the 15 MXD chronologies, representing sites with relatively strong cooling, reveals a considerably reduced response to volcanic forcing compared to the fully-sampled NH mean temperature. Using the reconstructed temperatures as response estimates, the summers were only 0.28°C (0.16°C) cooler in the first (second) year following an eruption. If local gridpoint temperatures for the 15 proxy sites are used as inputs in a pseudo-reconstruction, the observed cooling is similarly weakened: -0.28°C and -0.14°C, respectively for the first and second years.

As these findings contradict the overestimation of cooling found on local scale (Fig. 1e), we recomputed the pseudoreconstruction based on observational data using a randomized site selection scheme. This approach should result in a balanced mix of reconstructions that over- as well as underestimate volcanic cooling with a relatively even distribution around the actual cooling anomaly. The majority of pseudoreconstructions, however, exhibited less volcanic cooling than the overall average (Fig. 2).  Even doubling the number of input records to a total of 30 sites does not change this result.

## Discussion

Investigating the spatial pattern of summer temperature in response to volcanic eruptions revealed that some regions are not cooling despite massive releases of radiation absorbing sulphate into the stratosphere. The warming in central Asia and western North America is somewhat questionable, however, as data coverage is particularly sparse in these regions and the signal mainly reflects conditions in response to a single eruption (the 1960's eruption of Agung), which caused no clear cooling spike in the NH mean. Some of the observed temperature changes are certainly not significant considering the small number of studied events and uncertainties in the temperature field, i.e. cooling patternsmight change if a larger number of events were included (Esper et al. 2013). Nevertheless, the displacement of cooling in the second year is of particular relevance for a potential bias induced by an uneven spatial distribution of proxy records:  While in the current network,average cooling at the 15 proxy-sites was much stronger than the NH average in the first year, the values agreed much better in the second year. This indicates that a proxy network that appropriately represents cooling in the second post-eruption year is not necessarilyaccurate in the first year.

Spatial assembling and processing of the proxy data is an additional source of uncertainty. For the events in 1883, 1902, and 1912, pseudoreconstructions suggest a systematic underestimation of cooling, which is rarely found in years without volcanic forcing. Even the cold anomaly in 1907 (Fig. 2) can be ascribed to a volcanic eruption (Ksudach, Russia). There are also short periods of warmth that are difficult to reproduce with any proxy network. Thisphenomenon, however, cannot be associated with a common driver.

A reason for the underestimation of post-volcanic cooling in sparse proxy networks can be a more spatially homogeneous temperature field when external forcing is active. A reduced percentage of internal variability in such years results in less noise cancellation when calculating large-scale averages and thereby an enhanced temperature peak with respect to long-term variance. For a proxy network of limited spatial coverage, noise cancellation is less effective and, thus, the cooling peak less pronounced. This effect necessarily yields an underestimation of forced temperature changes when interpreting reconstructions based on a proxy network with limited spatial coverage using CPS or linear regression.

## Conclusion

Our analysis focused on potential biases in assessing the strength of volcanic forcing using proxy-based temperature reconstructions. At the local scale there is no systematic deviation from the instrumental recordin MXD-based temperature estimates, which is in line with the findings in Esper et al. (2015) who used a different set of volcanic events and similar proxy data. The hemispheric integration, as analyzed herein,revealed that there is no ideal spatial proxy distribution to prevent over- or underestimation of post-volcanic climatic cooling becausethe response pattern changes over time. The proxy network used in this study includes a bias towards regions with stronger cooling in the first year that abatesin the second year. A way to overcome this bias would be to drastically increase the number of predictor chronologies.

By merging data in large-scale reconstructions, it is likely that volcanic cooling is underestimated even if the proxychronologies are a perfect representation of local temperature and of the average NH climatic response. During years of volcanic activity, climate variability is additionally altered by external forcing, probably changing the spatial patterns in the temperature field resulting in different spatial characteristics of temperature anomalies that eventually suppress the volcanic signal in the proxy reconstruction. In contrast to the proxy distribution, this problem is not implicitly resolved using a denser proxy network, but it is possible to estimate the size of the effect by investigating the ratio between peak amplitude and the long-term variance.

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# SECTION 3

# ECOLOGY

# Differing growth response of *Celtis Africana* Burm.f.to climate variability: A case study from moist Afromontane forests in South Central Ethiopia

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## INTRODUCTION

Climate variability could change the forest landscape and vice versa (Van et al. 2009). Trees respond to these changes in different ways at different times. Dendrochronological studies on long-live tree species have the potential to provide long time series that reflect changes in climate conditions (e.g. Sass-Klaassen et al. 2008). Under most circumstances, tree growth is a function of climate variables such as precipitation (e.g. Gebrekirstos et al. 2008). Dendrochronology is a powerful tool to understand the spatial and temporal characteristics of climate influences on tree growth.

In this study, the relationship between climate variables and radial growth of *Celtis Africana* stocking in a seasonal climate in south central Ethiopia is investigated. The species selected for this study is believed to be economically important. Consequently, identifying the climate variables that significantly influence the radial growth dynamics of *Celtis africana* is vital to suggest suitable management options.

This study was carried out in Wondo Genet, where remnant forest that can be categorized as "Moist Afromontane" forests is found. The Afromontane forests in Ethiopia have experienced severe deforestation, fragmentation, loss of biodiversity and ecosystem impoverishment (Teketay et al. 2010). The forest in Wondo Genet is one of the few remnants of moist Afromontane forests in the south central highlands of Ethiopia (Kebede et al. 2012). The climate of the study area is characterized by a long rainy season from June to September and a short rainy season from March to May. Total annual rainfall ranges from 800mm to 1600mm, and average annual temperature from $18^\circ$C to $21^\circ$C. In most parts of the study site, Woinadega (sub-tropical) agro-climatic type prevails (Dessie & Kinlund 2007).
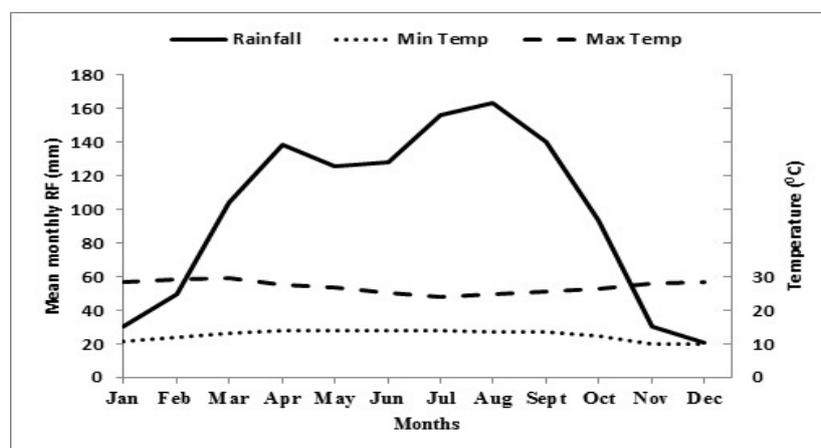


Figure 1: *Climate diagram of the study area based on climate data obtained from the National Meteorological Agency of Ethiopia (1983-2012)*

The study was conducted based on 15 stem discs collected at breast height (DBH, ~ 1.3m).The cross-sectional surface of the discs was sanded using progressively finer grades of sandpapers (60, 80, 120, 220, 320 and 600 grits) ensuring maximum visibility of anatomical features. Growth rings were detected by following concentric features around the stem circumference, and then identified when all rings on a disc and ring numbers and characteristics matched along different radii. Growth rings were marked and counted under a stereo-microscope on four radial directions of the sample discs. Tree-ring width was measured to the nearest 0.001 mm using a semi-automatic device, LEICA MS[5] microscope coupled with a LINTAB[TM] 5 digital measuring stage associated to TSAP-dos software, Rinntech, Heidelberg, Germany (Rinn 2003).

The samples were cross-dated using a combination of visual and statistical techniques following the method of Stokes & Smiley (1996). The visual cross-dating involves documenting characteristic patterns of pointer years (extreme wide and narrow rings) and matching these patterns between samples (Yamaguchi 1991). Furthermore, the similarity of individual curves were statistically tested considering the ''*Gleichlaufigkeitskoeffizient*'' (GLK) and *t*-values. Chronologies with *t*-values ≥ 4.0 and a mean GLK ≥ 85.0 (P < 0.001) were forwarded to climate-growth analyses (Enquist & Leffler 2001, Tolera et al. 2013). The statistical cross-dating was accomplished using COFECHA software (Holmes 1983). All cross-dated measurement series were then standardized to remove growth trends related to non-climate "noises" and to minimize effects of autocorrelation in the time series (Fritts 1976, Cook 1985). The program ARSTAN was used to produce a standardized tree-ring index chronology (Cook 1985). Each tree-ring series was detrended with a cubic smoothing spline of 32 years.

The climate-growth relationship was analyzed using monthly climate data from 1983 to 2012 obtained from the National Meteorological Agency (NMA) of Ethiopia. Simple linear regression analysis was used to examine how climatic variables influence radial growth of *Celtis africana*.

## Results and discussion

The transverse sections of *Celtis africana* showed that it forms less distinct growth rings. Wedging rings are prevalent. The microscopic cross-sections of the *species* revealed wood structures typical for hardwoods including diffuse porous vessel distributions. Though early wood and late wood growth boundaries exist in *Celtis africana*, it was too hard to distinguish between the two. The axial or vertical system is composed of rays, vessels of various sizes and arrangements, and axial parenchyma cells in various patterns and abundance. The growth ring boundary is formed by a thin band of marginal parenchyma cells.

The mean chronologies combining 15 trees (60 radii) were successfully cross-dated. The mean correlation against the inter-series correlation as calculated in COFECHA was 0.582, which was greater than the critical correlation level of 0.4093, (P < 0.05). This implies that the statistical cross-dating for the study species is highly significant.

*Celtis africana* showed significant relationships with the precipitation of the main rainy season and annual rainfall (Figure 2). Monthly correlation analysis also showed that rainfall during July had the highest positive and significant relationship with the tree-ring chronology signifying the importance of moisture availability for tree growth (Figure 3). Such findings corroborate with the results of other dendroclimatological studies in tropical areas (Grissino-Mayer & Butler 1993, Gebrekirstos et al. 2008, Couralet 2010).

The study species also showed better correlation with minimum temperature than maximum temperature, though insignificant (Figure 3). This suggested that temperature has some degree of influence on the growth of the study species.

y = 0.0082x - 0.2477
R² = 0.31  P < 0.05

y = 0.0067x + 0.2971
R² = 0.15   P < 0.05
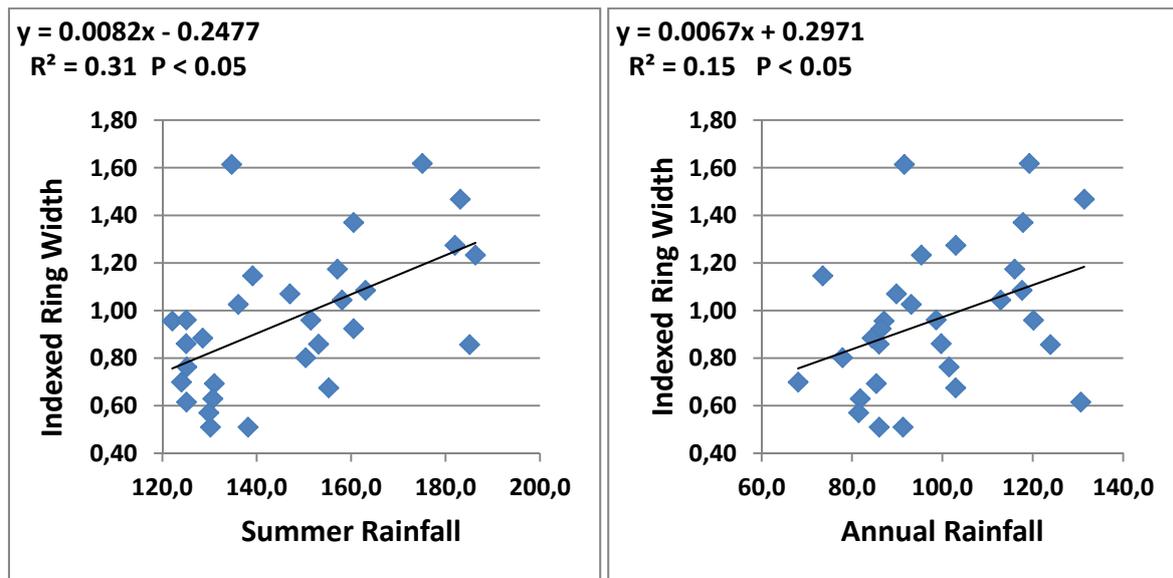
*Figure 2: Simple linear regression between indexed ring widths of Celtis africana and precipitation.*
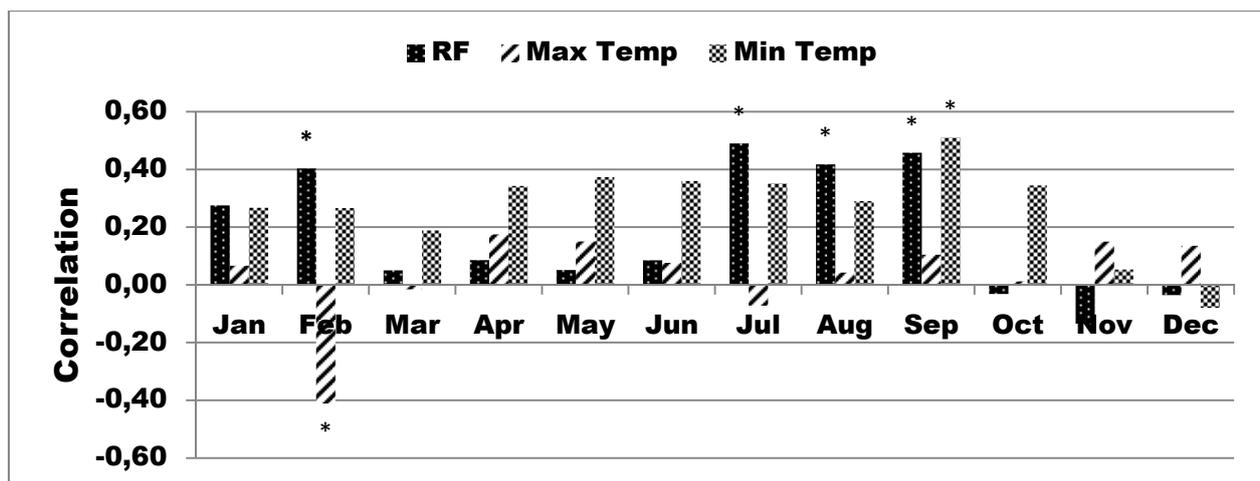


*Figure 3: Correlations between the 32-year spline detrended ring width chronology of Celtis africana and average monthly climate variables (\*: P < 0.05).*

## CONCLUSION

This study revealed the presence of anatomically distinct annual growth rings and statically validated cross-dating in *Celtis africana*. It is shown that growth of *Celtis africana* is influenced by the availability of moisture during main rainy season, particularly in July. *Celtis africana* is an useful species for more systematic dendrochronological studies in moist tropical regions in general and Ethiopia in particular.

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# Tree rings and masting: considering reproductive phenomena when interpreting tree rings?

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## Background and justification

Tree ring archives have provided key information for a diverse range of fields, including ecology, archaeology and palaeoclimatology. For example, the statistical relationships between growth and climate form the basis for tree-ring based reconstructions of climate, including regional and global temperature, drought frequency and severity, and atmospheric changes including ENSO and NOA (Cook et al. 2007). In addition, tree rings have been shown to be a reliable record of tree and forest aboveground biomass increment and ecosystem productivity (Babst et al. 2014), and therefore ecologists are increasingly using tree rings to investigate ecosystem dynamics and controls on tree and forest growth. For example, tree rings are being used to determine responses of forest growth to climate changes (Barber et al. 2000, Salzer et al. 2009). Other research is currently focused on the use of tree ring chronologies to detect the effect of increasing atmospheric $CO_2$ on tree growth in order to resolve outstanding questions concerning the carbon fertilisation effect on the terrestrial carbon sink (Peñuelas et al. 2011, Bowman et al. 2013). A key goal is to determine the sensitivities and vulnerabilities of different tree species to climate change, and predict how the key ecosystem services provided by forests will change in the coming decades. Linked to this, the relationships between growth and climate in tree ring networks have provided a rare opportunity to independently validate the output of Dynamic Global Vegetation Models (DGVMs) (Babst et al. 2013), for example by comparing predictions and observations of the response of forest growth to extreme climate events (Rammig et al. 2015).

Current interpretations of inter-annual variations in tree ring width are based on the assumption that tree growth is controlled by carbon supply and the processes of cell division and expansion (Fritts et al. 1991). These processes may be near-instantaneous (e.g. photosynthesis controlling carbon supply), or involve carry-over processes from previous years (e.g. remobilisation of carbon reserves). Because the rates and timings of these processes are all strongly influenced by weather conditions, strong relationships between ring width and climate can occur. However, in addition to these direct responses, a second class of processes related to resource allocation can also have an important control on annual growth (Thomas 2011). These have frequently been neglected when interpreting tree ring width variability. For example, allocation of resources to reproduction is highly variable, with seed production often varying strongly between years (Allen et al. 2014), and increasing through an individual's lifetime (Genet et al. 2010). Significantly for the interpretation of tree ring variability, allocation to reproduction is associated with a strong trade-off with growth (Obeso 2002), and is itself dependent on weather conditions. In particular, many tree species display strong inter-annual variation in allocation to reproduction (Schauber et al. 2002), a phenomenon known as masting. This allocation strategy typically involves synchronisation of heavy seed production across individuals (mast years), cued by particular weather conditions, with one or several subsequent years of low seed production. The climatic control of masting, combined with a trade-off between growth and reproduction (typically represented by a 20-50% reduction of growth in mast years) (Selas et al. 2002, Sanchez-Humanes et al. 2011, Hacket-Pain et al. 2015) introduces climate signals into tree ring chronologies, in addition to those directly related to primary

production (Fig. 1). However, the influence of allocation to reproduction has not been fully integrated in tree ring studies, despite the potential to explain a substantial component of the inter-annual variance in ring width.
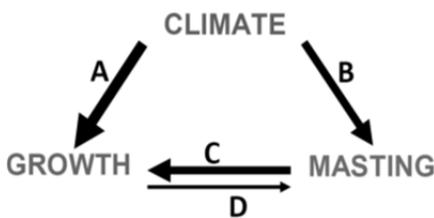


*Figure 1.* Sketch of the relationships between growth, masting and climate. The width of the arrows provides an indication of previous research effort. High frequency signals in tree rings are usually interpreted in terms of the direct effect of climate on growth (A). However, growth variations can also be caused by masting events (C), which can in turn create complex climate signals in tree ring chronologies as masting events are cued by climate (B + C). A further complication arises because masting behaviour may be influenced by resource availability (D).

**Tree rings and masting in *Fagus sylvatica* L.: a review of previous research**

We investigated the influence of inter-annual variations in allocation to reproduction on tree ring width index (RWI) chronologies in *Fagus sylvatica* (Hacket-Pain et al. 2015). We showed that, in mast years, allocation of resources to reproduction was associated with a 17-22% reduction in RWI during mast years, which occurred on average every five years. Other studies have reported similar reductions in ring width in beech during mast years ( von Jazewitsch 1953, Drobyshev et al. 2010, Latte et al. 2015), and in other species (for example, see the meta-analysis in Thomas 2011). Overall, we found that growing season climate (in this case a summer drought index) explained ~30% of the variance in RWI, but we could explain an additional ~20% by also accounting for masting in our model. We did not establish the physiological cause of the observed growth-reproduction trade-off, but we propose that a combination of direct and indirect trade-off mechanisms may be responsible for the observed reduction in RWI. In a direct trade-off, the increase in investment of carbohydrates in reproductive tissue in mast year reduces the carbohydrate available for woody tissues. Campioli et al.(2011) and Muller-Haubold et al. (2013) found that while growing season weather conditions are the main control of interannual variations in Gross Primary Productivity (GPP) and Net Primary Productivity (NPP) in beech forests, weather conditions in the previous year (previous summer temperature, the main cue for mast events) were the main control on the partitioning of NPP between the wood and fruits, and thus the ratio between GPP and wood NPP. This implies that while growing season weather conditions are the primary control on carbon assimilation (and thus, presumably, carbon availability), masting is a key control on how much of this carbon is allocated to wood production, and hence the width of the resulting tree ring. However, this trade-off between allocation to fruit production and growth may only be seasonal, limited to periods when GPP is low and carbon demand for fruit production is high (i.e. the start of the growing season) (Mund et al. 2010).In addition to influencing the allocation of available carbon (a direct trade-off), mast years may reduce ring width indirectly by reducing GPP, and consequently reducing overall carbon availability (including carbon for growth). Developing fruits are a strong sink for nutrients (Ichie et al. 2005; Sala et al. 2012), with high seed production associated with reduced nitrogen concentration in seed bearing shoots (Alla et al. 2012) and reduced photosynthetic capacity (Han et al. 2008). Furthermore, mast years are associated with smaller whole-plant leaf area (Ferretti et al. 1998; Innes 1992), due to a combination of a lower leaf number and reduced leaf size (Thomas 2011). Together, this reduction in leaf area, and lower photosynthetic capacity as a result of lower foliar nitrogen concentrations may result in reduced carbon assimilation and thus carbon availability.

In addition to demonstrating the strength of growth-reproduction trade-offs in *F.* sylvatica, and the potential to explain significant proportions of variance in ring width by incorporating information on masting behaviour, we have also demonstrated the potential for masting to introduce distinct climate signals into tree ring chronologies (Fig. 1). Mast years are associated with particular weather cues, which in *F. sylvatica* are most commonly reported to be a sequence of cool

temperatures in the summer two years previous, followed by warm temperatures in the summer prior to the mast year (Drobyshev et al. 2010, Hacket-Pain 2013). Importantly, we show that the combination of this climatic cue for mast years, and the strong growth-reproduction trade-off, creates specific correlations between RWI and climate (Piovesan & Schirone 2000, Hacket-Pain et al. 2015). In the case of *F. sylvatica,* we showed that correlations between RWI and previous summer temperature can be explained by this masting-related mechanism (Hacket-Pain et al. 2015). This result has important implications for the interpretation of growth-climate relationships in *F. sylvatica*, particularly as these lagged correlations with previous summer temperature are the most commonly reported correlations in beech RWI chronologies (Hacket-Pain et al. In Prep). However, the results also have wider implications, as lagged correlations between ring width and summer climate of previous years are commonly reported for many species (Wettstein et al. 2011, Babst et al. 2013). Additionally, climates cues of mast years, and growth-reproduction trade-offs have been reported for many tree species (e.g. Selas et al. 2002, Speer et al. 2009, Thomas 2011, Redmond et al. 2012), indicating that a similar mechanism, is likely to also apply in other key tree species used in dendrochronological studies.

Furthermore, any interaction between masting and tree growth should also be dependent on tree age as seed production increases as trees become older (and larger) (Nilsson & Wastljung 1987, Genet et al. 2010, Viglas et al. 2013). Consequently, as juvenile trees invest relatively little in seed production, they should respond less to the temperature of the previous summer than mature trees producing heavy seed crops. This would explain the common observation of increasing correlation between RWI and previous summer temperature in *F. sylvatica* chronologies (Di Filippo et al. 2007, Drobyshev et al. 2010, Hacket-Pain 2013), and also the strong relationship between tree age and these lagged correlations that we report in a meta-analysis of published growth-climate relationships in *F. sylvatica* (Hacket-Pain et al. In Prep).

## Identification of knowledge gaps and justification for future research

Our study was based on only one regional tree ring chronology and masting dataset, and so the significance of these findings more generally is unknown. We know that allocation strategies, including allocation to reproduction, vary between species, resource availability (i.e. climate) and tree age ( Schauber et al. 2002, Genet et al. 2010, Allen et al. 2014, Roland et al. 2014), but the impact of these variations on tree growth and hence tree ring archives is poorly understood. It is likely that allocation to reproduction will influence not only growth-climate relationships, but also other key tree ring 'signals', which are widely used to quantify growth variability and the response of growth to climate (summarised in Table 1 and Figure 2). Furthermore, the potential for masting to influence variation in ring width depends on both the strength of the growth-reproduction trade-off and masting phenomena, including the specific weather cue and the typical return time of mast years, and the size of the seed crop associated with mast years. These processes are poorly understood, but are expected to vary according to: (i) species, (ii) resource availability, and (iii) tree age. We expect these factors to result in strong species-specific spatial and temporal variations in the importance of masting for tree rings, but this has not been considered in the literature. Below we detail the potential ways in which these three factors could influence tree ring signals through masting behaviour:

### (i) Species

Physiological differences between species result in different strengths in the growth-reproduction trade-off, which in turn controls the potential for allocation to reproduction to influence tree growth and ring width. Relevant physiological differences include the size and number of seeds produced in mast years (i.e. the reproductive sink strength), the typical interval between mast years, and timing and duration of fruit maturation. Additionally, the specific weather cues for masting and the strength of the association between cues and mast years may vary between species.

Consequently, the strength and patterns of tree ring signals introduced into tree ring chronologies by allocation to reproduction will vary between species.

*(ii) Resource availability*

The effect of resource availability (e.g. light and soil nutrients) on the influence of masting on tree ring chronologies is likely to be complex. For example, the literature indicates that as growing conditions become increasingly marginal, masting becomes less frequent and seed crops become smaller (Allen et al. 2014). Consequently we hypothesise that in climatically marginal regions the effects of masting on tree rings may be reduced. On the other hand, stronger trade-offs are expected when resources are more limiting. The overall effect is likely to result in spatial variation in the influence of masting on tree rings, and also variation in time if growing conditions and resource availability change. The magnitude of these effects is currently unknown but likely significant, with important implications. For example, tree ring-based reconstructions of climate usually rely on populations of trees growing in climatically marginal areas, and it is therefore important to understand the relative sensitivity of these chronologies to the complicating effects of masting.

*(iii) Tree Age*

Resource allocation changes according to tree age. Older trees mast more regularly than younger trees, and allocate proportionally more resources to seed production in these mast years (i.e. they mast more regularly and more heavily) (Genet et al. 2010, Viglas et al. 2013). Consequently, the effect of masting on tree rings should increase with tree age. This is important because age-related changes in masting may explain temporal changes in ring width and tree ring signals such as growth-climate relationships. In previous research we found indirect evidence of this effect, with masting-related growth-climate relationships in *F. sylvatica* stronger in older trees ( Hacket-Pain et al. 2015, Hacket-Pain et al. In Prep). However, direct evidence of the influence of tree age is still lacking, particularly for the widely used signals summarised in table 1. This is important because tree age at the time of ring formation usually varies with time along a chronology, creating the potential for age-related biases in reconstructions. Numerous studies have compared the relationships between ring width and climate in cohorts of trees of different ages (Esper et al. 2008), but few studies have explicitly tested for an effect due specifically to age-related physiological processes.

*Tree ring signals and masting*

While the importance of allocation strategies for tree growth and tree ring chronologies can be appreciated in general terms, several key uncertainties remain. For example, while some studies directly rely on the analysis of raw tree ring data, many ecological and biogeographical studies use derived statistics to quantify components of tree ring variability (tree ring 'signals'), summarised in table 1. These include measures of the interannual variability in ring width, and the frequency of extreme growth anomalies ('pointer years'). All of these are used to assess stress in tree populations and the responses to climate variations (e.g. Lenz et al. 2014; Latte et al. 2015), and have the potential to act as early-warning signals for tree/forest mortality events and ecosystem collapse (Suarez et al. 2004, Scheffer et al. 2009, Linares et al. 2010). Lower-frequency variations in growth such as decadal growth trends are also used to detect and monitor forest health, while growth-climate relationships and the responses of growth to climate extremes are used to understand which climatic factors drive these changes in growth. However, the potential role of masting in influencing these signals in poorly understood. For example, previous research has shown that mast years have a tendency to cluster, particularly during periods of more variable climate (Drobyshev et al. 2014). This may introduce two important signals into tree ring

chronologies which are often interpreted as indicating forest decline: increased variation in ring width and negative trends in growth (Fig. 2).
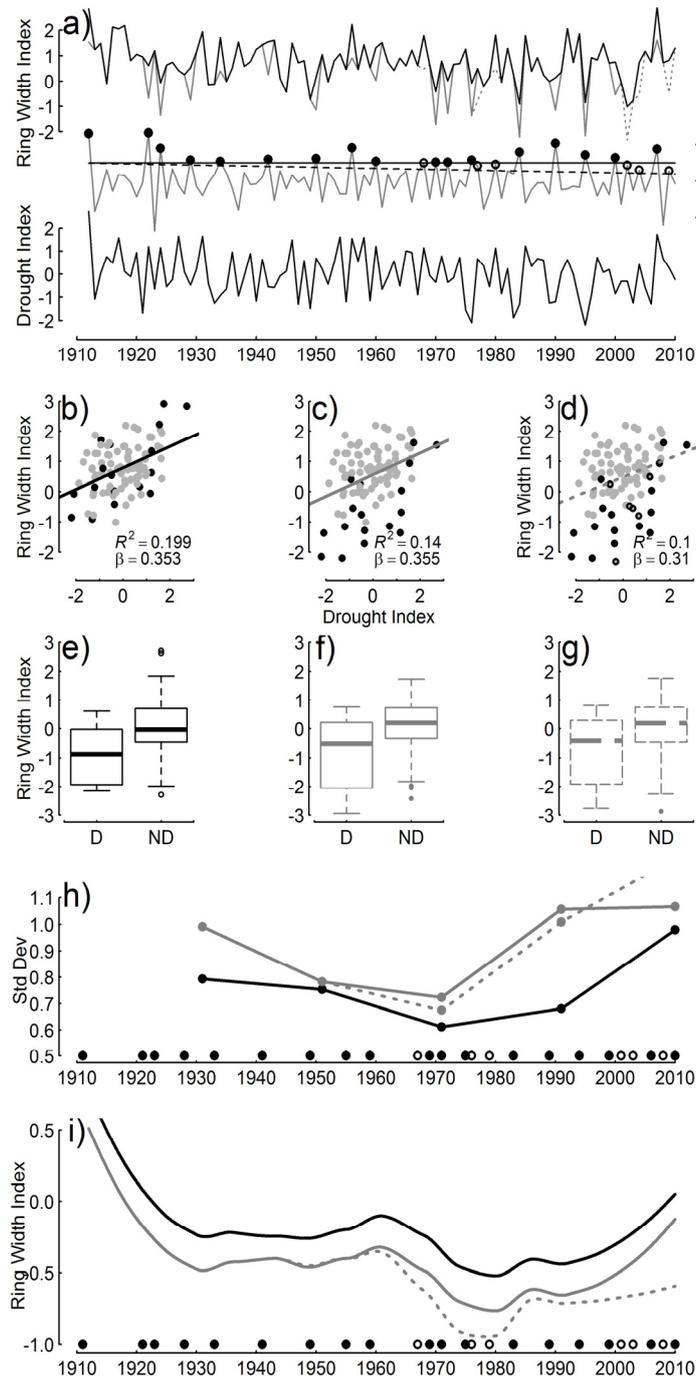


*Figure 2: Overview of possible effects of masting on tree rings, using simulated data.*
***a)*** *RWI (black line) was simulated using an index of summer drought and random noise. Two modified RWI chronologies were also created that included a growth reduction in mast years. Mast years were predicted as a function of ΔT (T$_{JUL-1}$ − T$_{JUL-2}$), with either a constant threshold (solid line, filled points, corresponding to the solid grey RWI curve) or a decreasing threshold (dashed line, filled and empty points, corresponding to the dashed grey RWI curve). The declining threshold for mast events was a simplification to simulate increasing frequency of masting with tree age.* ***b-d)*** *Relationships between RWI and summer drought index b) RWI, c) RWI with mast years, d) RWI with mast years from decreasing threshold. Growth-climate relationships change despite no direct relationship between mast events and drought. Additionally, increases in mast frequency/intensity may act to reduce the strength of the growth-climate relationship through time, as an increasing percentage of variance is explained by masting events rather than drought (not shown).* ***e-g)*** *RWI in drought and non-drought years for the three chronologies. The drought group includes the 10 driest years in the drought index. If drought years tend to coincide with mast years or non-mast years, the apparent reduction in growth associated with drought may be overestimated or underestimated respectively.* ***h)*** *Growth variability in the three chronologies (standard deviation), calculated for 20-year windows. As mast years are associated with low RWI, trees that mast more frequently have greater growth variability. i) Growth trends for the three chronologies, represented using loess curves. Periods of more intense masting correspond to lower growth and potentially negative growth trends. If masting increases in frequency/intensity with age then this may influence long-term growth trends.*

Also, while greater variability in ring width is normally taken to indicate increased direct impacts of climate on growth (e.g. through greater drought frequency), this response might actually be due to more frequent mast years (e.g. driven by climatic changes or aging), despite there being no increase in tree stress (Fig. 2). Additionally, a cluster of narrow rings resulting from a cluster of mast years (caused by a period of increased climate variability, for example) may also create a multi-year reduction in growth, despite no actual decline in vitality (Fig. 2).

*Table 1:* *Possible effects of masting on the interpretation of tree ring archives.*

| Tree ring signal | Masting effect on tree ring chronology interpretation |
|---|---|
| Growth-climate relationships | *In F. sylvatica, correlations between growth and previous summer temperature are created by weather-cued masting (Hacket-Pain et al. 2015). Similar effects are expected for other species (Selas et al. 2002), but have not yet been demonstrated. Correlations between growth and growing-season climate may also be affected (Figure 3 b-d).* |
| Event years (extreme climate years) | *The response of trees to known individual years of extreme conditions will be influenced if a mast year coincides. As mast years may not be synchronous across species or across space, this complicates comparisons of the response of different populations to extreme events.* |
| Negative pointer years | *Mast years are associated with reduced growth, and so extreme narrow rings are created when drought coincides with mast years. Additionally, strong mast years may result in strong growth reductions in the absence of severe climate conditions during the growing season. If allocation to reproduction is dependent on tree age or resource availability, then the frequency of negative pointer years in a chronology may not be a direct measure of tree stress.* |
| Interannual growth variability | *Inter-annual growth variability is summarised using statistics such as standard deviation, mean sensitivity or the Gini coefficient. It is expected to increase when masting is more frequent (Figure 3 h). Increases in growth variability may therefore be expected as trees become older. Additionally, variations in growth variability between populations may be created by differences in tree age.* |
| Growth trends | *Periods of more frequent or intense masting may be associated with lower average growth and negative growth trends. Additionally, increased frequency or intensity of masting with age may be a contributing factor to long-term declines in growth.* |

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# On the occurrence of cyclic larch budmoth outbreaks beyond its geographical hotspots

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## Introduction

One of the most intensively investigated and probably best-documentedcyclic behaviourin ecological systemsare regularlarch budmoth (*Zeiraphera diniana* [Gn.]; LBM) mass outbreaks (Berryman 1996, Baltensweiler et al. 2008), which occur every 8-10 years in travelling wavesacross most of the European Alps (Baltensweiler 1993). Periodical mass outbreaks of this foliage-feeding insect are mainlyrestricted to itshost species, the European larch (*Larix decidua* Mill.). Suitable habitatscoverthe subalpine zoneof the central Alpine arc (Baltensweiler et al. 1977), with the optimum elevational zone of outbreak foci being estimated to 1700-2000 m asl (Baltensweiler et al. 2008, Johnson et al. 2010).Due to mass outbreaks, larch trees discolorate and might completely defoliate(Baltensweiler et al. 1977).This tree defoliation generally reduces radial growth significantly during and after an outbreak year so that LBM events leave distinct fingerprints in tree-ring width and density (Schweingruber 1979, Esper et al. 2007, Baltensweiler et al. 2008, Büntgen et al. 2009, Johnson et al. 2010). The resulting patterns allowed reconstructinga 1200-year long record of LBM mass outbreaks in Swiss subalpine valleys(Esper et al. 2007), as well as a 300-year record with a wider spatial coverage(Büntgen et al. 2009).

Otherstudies assessedthe mechanisms ofthe varying LBM density including the drivers of itscyclicity(e.g. Fischlin & Baltensweiler 1979, Anderson & May 1980, Baltensweiler 1993, Turchin et al. 2003),as well as the synchronicity of outbreak events across the Alps (e.g. Bjørnstad et al. 2002, Johnson et al. 2004, Price et al. 2006). All of these investigations focused on the well-known outbreak regions in the centre of the Alps. However, the natural distribution range of the host species European larch (Fig. 1) clearly exceeds these LBM hotspot regions and it remains unclear to which extendregular LBM cycles also occur at the edge of the host's distribution range, and through which environmental factors outbreak regions are spatially constraint. A recent study, for instance, revealed theabsence of cyclic LBM mass outbreaks in the Tatra Mountains (Konter et al. 2015a).

Here, we test for the occurrence of cyclic LBM outbreaks in severalaltitudinal belts of different larch habitatsacross the Western and Northern Alps, as well as the Tatra Mountains.

## Material and Methods

### Study design

Tree-ring data from three different European larch habitats were used in this study (Fig. 1, Table 1). The Western Alps belong to the main distribution range of European larch and represent a LBM hotspot.Eleven sites were sampled ranging from 985-2200 m asl. The Northern Alps constitute the edge of the larch core habitatand information about LBM mass outbreaks is missing.In this region,18 stands were sampled, encompassing different altitudes from 527-1670 m asl. In the Tatra Mountains, representing a disjunctive habitat of larch, cyclic LBM outbreaks were recently reported to beabsent (Konter et al. 2015a,b). Data from two sites in 950 and 1500 m asl were used for control.

At each site, ten dominant larch trees were coredtwice at breast height. After TRW measurement, using TSAP-Win scientific software and a LINTAB 6 measurement device (Rinn 2003), cross-dating accuracy was verified visually and statistically using COFECHA (Holmes 1983). Descriptive statistics of raw chronologies include the mean segment length (MSL), average growth rate (AGR) and first-order autocorrelation (lag-1). Inter-series correlation (Rbar) and expressed population signal (EPS) were calculated to estimate the internal coherence of the chronologies (Table 1).
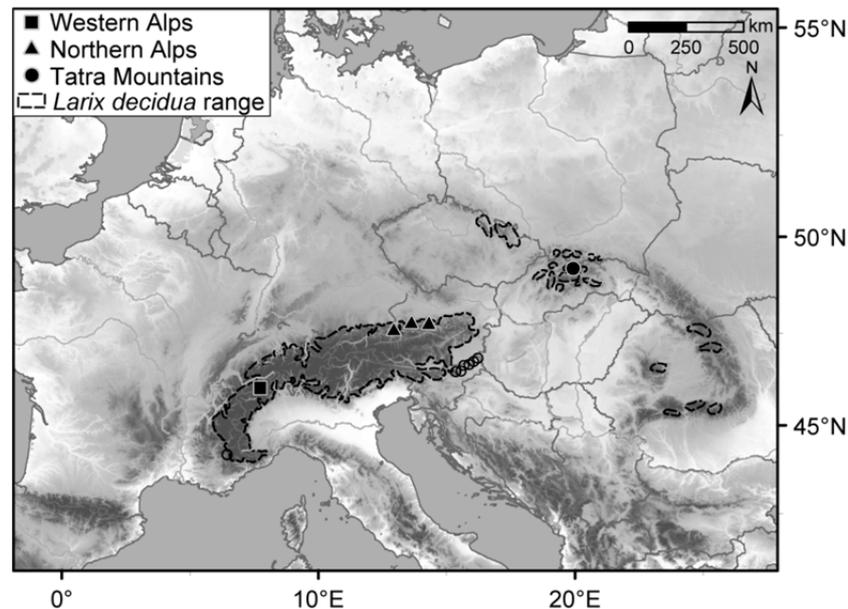


*Figure 1: Map showing the location of the sampling sites in the Western Alps (square), Northern Alps (triangles), and Tatra Mountains (circle) together with the natural distribution range of Larix decidua (dashed line). Distribution data was compiled and provided by E. Welk, AG Chorology, Geobotany Department University Halle, based on map 21b in Meusel et al. (1965).*

*Chronology building and time series analyses*

Raw ring width data weretransformed into indices to remove age and size related growth trends and potential disturbance signals (e.g., forest management). To emphasize high-frequency variability,a cubic smoothing spline with a frequency cut-off of 50% at 30 years was applied to the individual series (Cook & Peters 1981). Site chronologies were built by averaging the detrended single series usinga robust mean (Mosteller & Tukey 1977), truncated at a minimum replication of 5 series.

To explore cyclical patterns in the individual site chronologies, potentially caused by LBM outbreaks, spectral analysis was applied. The red-noise spectra were estimated, computing the spectrum of each time-series using the Lomb-Scargle Fourier transform (Schulz & Mudelsee 2002). A continuous wavelet transform of the time series was further used considering the Morlet wavelet as a base (Torrence & Compo 1998) to assess potential variations over time.

All statistical procedures were performed using R 3.1.1 (R Development Core Team 2014) and the package dplR (Bunn et al. 2012).

**Results**

Descriptive chronology statistics indicate comparable datasets among the larch habitats (Table 1). MSL of larch chronologies ranges from 78-216 years in the Western Alps, and 92-271 years in the Northern Alps. Trees in the Tatra are older reachingMSL of ~230 years. Larch AGR in theWestern Alps (0.67-1.56 mm) is slightly lower than in the Northern Alps (0.72-2.00 mm) and lowest in the Tatra Mountains (0.57-0.76 mm), representing the varying age structure of trees in the different regions. Lag-1 autocorrelation is high in all larch habitatsranging from 0.67-0.89. Rbar values show

distinct coherency among individual TRW series inall chronologies and range from 0.60-0.74 in the Western Alps, 0.54-0.74 in the Northern Alps, and 0.71-0.77 in the Tatra Mountains, demonstrating highest internal coherence in the latter. EPS values of all larch sites exceed the widely accepted threshold of 0.85 (Wigley et al. 1984), indicating sufficient internal signal strength inall investigated sites.

*Table 1: Location and characteristics of raw larch site chronologies sorted by elevation within a region.*

| Region | Lat. | Lon. | Altitude (m asl) | Period | MSL (years) | AGR (mm) | Lag-1 | Rbar | EPS |
|--------|------|------|------------------|--------|-------------|----------|-------|------|-----|
| W-Alps | 46°18' | 8°00' | 985 | 1924-2011 | 83 | 1.30 | 0.80 | 0.74 | 0.97 |
| | 46°18' | 8°00' | 1100 | 1907-2010 | 87 | 1.47 | 0.75 | 0.67 | 0.93 |
| | 46°12' | 8°04' | 1400 | 1928-2010 | 78 | 1.56 | 0.66 | 0.62 | 0.96 |
| | 46°12' | 8°03' | 1575 | 1875-2011 | 131 | 1.13 | 0.79 | 0.60 | 0.97 |
| | 46°12' | 8°03' | 1712 | 1898-2011 | 108 | 1.33 | 0.79 | 0.67 | 0.97 |
| | 46°12' | 8°03' | 1713 | 1879-2010 | 105 | 1.09 | 0.75 | 0.61 | 0.95 |
| | 46°11' | 8°03' | 1900 | 1847-2010 | 118 | 1.19 | 0.69 | 0.69 | 0.93 |
| | 46°13' | 8°03' | 2020 | 1844-2010 | 130 | 0.93 | 0.76 | 0.66 | 0.96 |
| | 46°13' | 8°04' | 2150 | 1771-2009 | 167 | 0.67 | 0.70 | 0.65 | 0.93 |
| | 46°00' | 7°45' | 2200 | 1816-2011 | 135 | 1.39 | 0.66 | 0.71 | 0.94 |
| | 46°01' | 7°46' | 2200 | 1762-2011 | 216 | 0.91 | 0.73 | 0.73 | 0.96 |
| N-Alps | 47°47' | 13°33' | 527 | 1828-2010 | 174 | 1.24 | 0.89 | 0.63 | 0.98 |
| | 47°40' | 13°01' | 760 | 1850-2008 | 149 | 1.11 | 0.85 | 0.57 | 0.96 |
| | 47°50' | 14°27' | 894 | 1914-2010 | 93 | 1.91 | 0.87 | 0.57 | 0.98 |
| | 47°50' | 14°26' | 901 | 1916-2010 | 92 | 2.00 | 0.88 | 0.63 | 0.99 |
| | 47°45' | 14°21' | 950 | 1830-2009 | 172 | 1.08 | 0.84 | 0.60 | 0.97 |
| | 47°38' | 12°51' | 1040 | 1838-2008 | 163 | 1.21 | 0.84 | 0.60 | 0.95 |
| | 47°31' | 12°47' | 1080 | 1889-2008 | 110 | 1.57 | 0.79 | 0.64 | 0.96 |
| | 47°45' | 14°26' | 1150 | 1829-2009 | 173 | 1.05 | 0.84 | 0.59 | 0.97 |
| | 47°31' | 12°47' | 1250 | 1803-2008 | 183 | 1.22 | 0.87 | 0.55 | 0.94 |
| | 47°33' | 12°48' | 1310 | 1832-2008 | 164 | 1.16 | 0.81 | 0.60 | 0.96 |
| | 47°35' | 12°53' | 1330 | 1806-2008 | 185 | 1.09 | 0.84 | 0.58 | 0.97 |
| | 47°46' | 14°25' | 1350 | 1855-2009 | 144 | 1.37 | 0.85 | 0.54 | 0.97 |
| | 47°46' | 14°25' | 1460 | 1847-2009 | 145 | 1.21 | 0.79 | 0.58 | 0.94 |
| | 47°49' | 13°35' | 1500 | 1785-2010 | 193 | 0.89 | 0.71 | 0.73 | 0.95 |
| | 47°33' | 12°48' | 1560 | 1780-2008 | 165 | 1.28 | 0.74 | 0.61 | 0.93 |
| | 47°34' | 12°49' | 1600 | 1706-2008 | 271 | 0.72 | 0.74 | 0.74 | 0.97 |
| | 47°34' | 12°49' | 1620 | 1747-2008 | 244 | 0.85 | 0.81 | 0.65 | 0.96 |
| | 47°31' | 13°01' | 1670 | 1781-2008 | 193 | 1.18 | 0.82 | 0.66 | 0.97 |
| Tatra | 48°55' | 20°15' | 950 | 1767-2012 | 230 | 0.57 | 0.68 | 0.71 | 0.97 |
| | 49°09' | 20°04' | 1500 | 1770-2012 | 232 | 0.76 | 0.67 | 0.77 | 0.98 |

Analyses of the frequency spectrum show distinct differences of cyclic reoccurrences of potential LBM outbreaks among the larch habitats (Fig. 2). The Western Alps chronologies indicate a significant periodicity between ~8 and 10 years at elevations above 1900 m asl (at two subalpine sites also between 21 and 24 years). The period length of spectral peaks increases towards lower elevations, reaching significanceat 7 to 10 years in 1400-1700 m asl, and 11 to 16 years in 1100 m asl. The low-elevation site shows no indication for LBM cyclicity. In the Northern Alps, a variety of spectral peaks occur without a clear dependence on elevation. At nine sites significant periodicity

can be detected in the high-frequency domain around 2.5 to 4 years. At seven sites a 6 to 7 year cycle is present, culminatingat altitudes above 1300 m asl. Single additional, significant peaks occur between 11 and 25 years. In the Tatra Mountains, significant cycles only appear in the high frequency domain of 2 to 3 years.
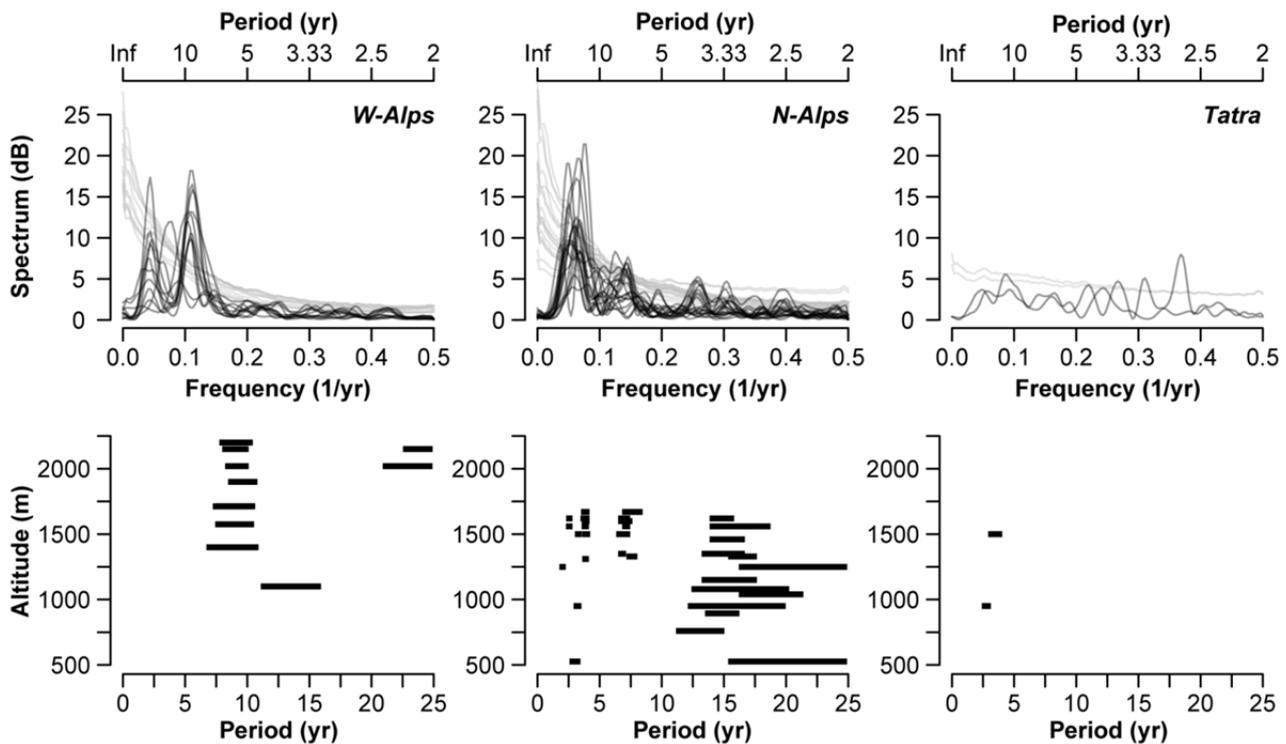


*Figure 2: Red-noise spectra of Western Alps (left), Northern Alps (centre) and Tatra Mountain (right) larch chronologies (upper panels) calculated over 1860-2008. Light colours indicate the 95th percentile red noise spectra. Bottom panels show the periods with significance ordered by elevation.*

The wavelet analysis again reveals distinct dissimilarities of potential LBM periodicity in the differing larch habitats (Fig. 3). In the Western Alps, significant power at ~8 years is almost continuously present for all chronologies above 1400 m asl with a short interruption between ~1910-1930. Significant cyclicity with wavelengths of 16-32 years exists almost over the entire period. In the 1000-1400 m belt, the 1400 m asl site shows a ~8 year cycleonly. The sites below this threshold provide no clear indication for a persistent and regular LBM cycle. In the Northern Alps the picture is quite diffuse. There is no clear sign for periodic LBM oscillations. In the high altitudinal belt, a significant 8 year cycle existsover a relatively short period from around 1910-1950. Some single sites in the 1000-1400 m belt show this pattern as well and even in the lowest altitudes the ~1950 events appear. The larch trees in the Tatra Mountains again reveal no evidence for a typical LBM cycle.

## Discussion

Cycles of the LBM mass infestation are intensively investigated in the core habitat of its host species European larch (cf. Baltensweiler 1993, Baltensweiler & Rubli 1999, Bjørnstad et al. 2002, Johnson et al. 2004, Price et al. 2006, Esper et al. 2007, Baltensweiler et al. 2008, Büntgen et al. 2009, Johnson et al. 2010, Battipaglia et al. 2014). However, all these studies focus on the main LBM outbreak region, although the distribution range of larch exceeds these well-known hotspot areas. The drivers for cyclic LBM events are still not fully understood (Johnson et al. 2010), and their regular occurrence remains particularly debatable towards the margin or even beyond the host's main distribution (Konter et al. 2015a). We here assessed indications for a cyclic pattern of

LBM at the edge of the core habitat of larch and compared it to a LBM hotspot area (the Western Alps), and a region wherecyclic LBM mass outbreaks are likely absent (the Tatra Mountains).
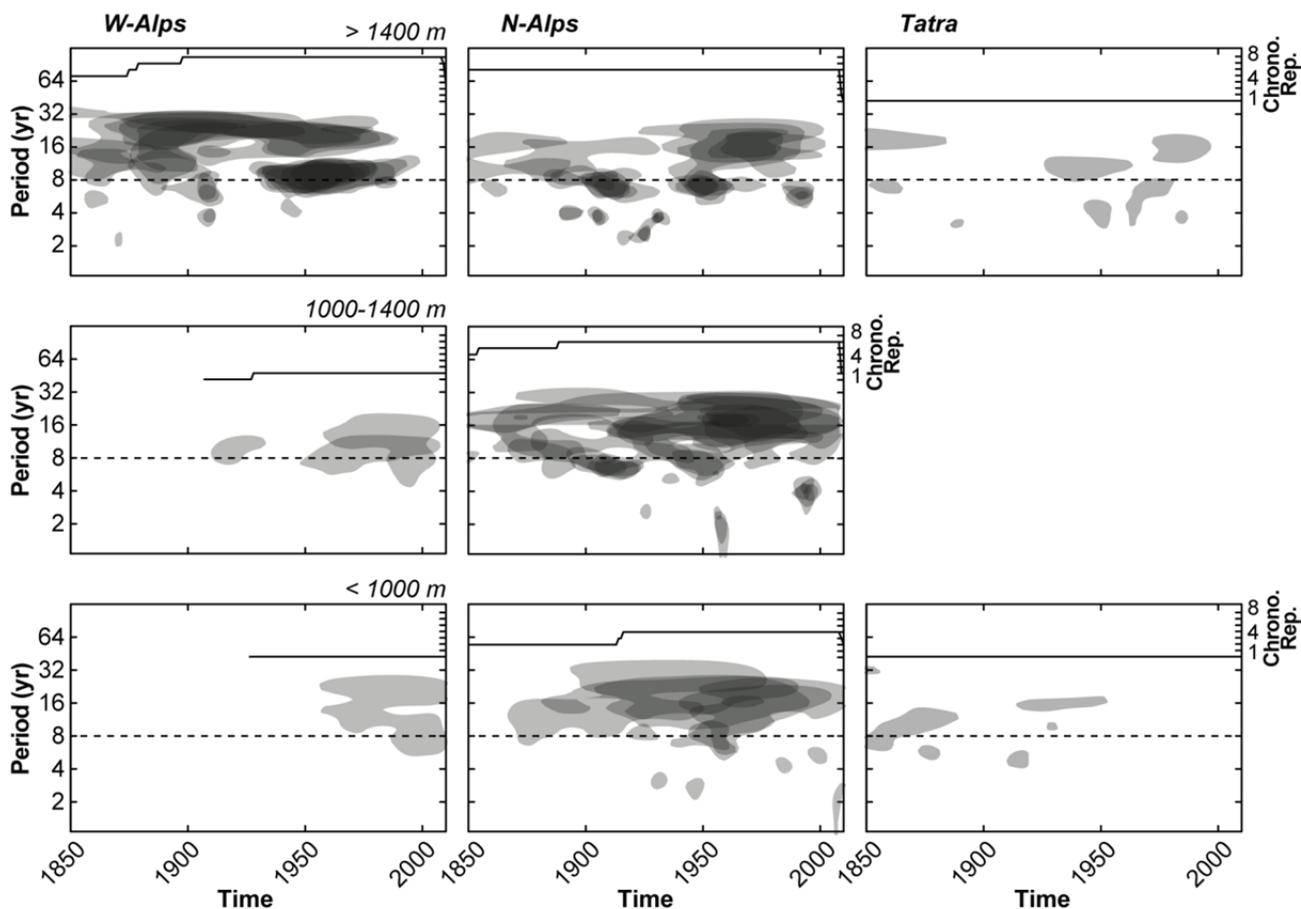


*Figure 3: Superimposed wavelet power spectra of the Western Alps (left), Northern Alps (centre) and Tatra Mountain (right) larch chronologies subdivided for different altitudinal belts (> 1400 m: upper panel, 1000-1400 m: central panel and < 1000 m: lower panel). Only significant (95%) wavelet power is plotted and with high opacity factor, i.e. dark colours indicate overlapping significant wavelet power of different chronologies (note chronology replication [= Chrono. Rep.] at the upper part of each box).*

Our results confirm that altitudes above 1700 m asl seem to be the optimal elevational zone for regular outbreaks (Johnson et al. 2010) where we found a distinct 8-10 year cyclicity in the Western Alps. However, regular LBM outbreaks also occurred down to 1400 m asl, but the temporal pattern is less persistent and distinct. For the Northern Alps, at the edge of the hosts' distribution range, we found some evidence for LBM outbreaks in ~1910s and ~1950s, but the pattern is not persistent over time. Surprisingly, there are outbreak indications even at lower altitudes. This might be explained by the climatic conditions in the differing habitatsanalysed here. Temperatures in the Northern Alps are lower compared to the Western Alps, as indicated by differing treeline elevations ranging from ~1800 m asl in the north (Ewald 2012) to 2200 m asl in the west (Brändli 1998). This might mean that the climatic envelope should allow the occurrence of regular LBM mass outbreaks in the Northern Alps, even at lower altitudes.
We here tested the cyclicity of LBM events in differing larch habitats but the drivers for the presence or absence of periodic mass outbreaksstill remain unclear. Further research is needed investigating the climate and ecological envelope in the different larch habitats in more detail.

## Acknowledgments

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# Can microsite effects explain divergent growth in treeline Scots pine?

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## Introduction

Northern treelines are expected to reflect a strong summer temperature signal as they are generally cold-limited. Ring width datafrom northern treelines, and in particular Scots pine (*Pinus sylvestris* L.)from Fennoscandia, have thus frequently been used to build long chronologies in order to reconstruct climatic conditions of the past centuries (Esper et al. 2002, Grudd et al. 2002, Linderholm & Gunnarson 2005, Helama et al. 2009, McCarroll et al. 2013, Lindholm et al. 2014). Studies on *Picea glauca* (Moench) Vossin North America, however, have revealed diverging growth response as well as a loss of sensitivity to summer temperatures, suggesting that e.g. temperature-induced drought stress/reduced water availability might lead to reduced tree growth at northern treelines (Lloyd & Fastie 2002, Wilmking et al. 2004, Wilmking & Juday 2005, Driscoll et al. 2005, D'Arrigo et al. 2008, Porter & Pisaric 2011).Although less prevalent, divergent growth of Scots pinehas been found in some studies for Eurasia as well (e.g. Wilmkinget al. 2005, Lloyd & Bunn 2007, Seo et al. 2011). Recently, Düthorn et al. (2013, 2015) and Helama et al. (2013) have shownthat a different response to climatic conditions as well as different growth rates among adjacent pine stands in Fennoscandia might be caused by different microsite conditions: Late spring snowmelt might shorten the growing period for wet-standing lakeshore/riparian trees due to water oversaturation and lower ground temperatures, especially for juvenile trees. Overall, chronologies built from individuals with inconsistent response to climate (e.g. from different microsites) may lead to a misinterpretation of past climatic conditions as well as of models for carbon storage and release in boreal forests (e.g. Barber et al. 2000).

Inthispreliminary study, we therefore further investigate the hypothesis that microsite differences (in terms of water availability) influence tree growth by addressing the questions whether and to what extent microsite conditions (dry, wet, both ata northern and a southern location near the treeline) cause differences in (i) growth performance, (ii) climate–growth relationships (we expect dry sites being correlated negatively with summer temperature or positively with summer precipitation) and (iii) stability of climate–growth relationships.

## Materials and Methods

### Study area

We analysed 82 individuals of Scots pine from two differentlocations in northern Finland. The southern stand is locatedjust within the continuous distribution limits of Scots pine, near Laanila (68°30'N; 27°18'E, 260–280 m a.s.l.), while the northern stand is situated 135 km further north near lake Kenesjärvi (69°41'N; 27°6' E, 180–200m a.s.l., about 10 km south of Kevo Subarctic Research Institute of the University of Turku), where islands of closed pine stands still occur. In each of the two stands, sampling was carried out in two differingmicrosites: Sites on lakeshores (Laanila) and large scale depressions (Kenesjärvi) were defined as wet sites (LW, KW), whereasadjacent well-drained south to south-west facing slopes were considered dry sites (LD, KD). Based on differences in topography and ground vegetationwe assume that trees from wet

sites have permanent access to groundwater, while trees from dry sites might depend more on regular precipitation and snow melt.

*Tree-ring data*

Two cores per tree (A: 4.5mm, B: 12mm in diameter) perpendicular to each other were taken at breast height. After air drying, the surface of core A was cut using a WSL core-microtome (Gärtner & Nievergelt 2010) and scanned visually using a conventional scanner. Tree-ring widthwas measured from the optical images using Cybis CooRecorder (v. 7.7, Cybis Elektronik & Data AB) with 0.001mm precision. Core Bwas glued to a sample holder and cut to a lath of 1.25 mm thickness using a two-bladed circular saw (Dendrocut 2003, Walesch Electronics). Resin and other soluble substances were extracted by boiling the laths in 96% ethanol for 24 hours. After letting the samples dry, they were x-rayed using an ITRAX Multiscanner (Cox Analytical Systems) with an exposure time of 25 ms, an intensity of 30 kV/50 mA, and in steps of 20 µm. Ring width, as well as density (not presented here), was subsequently measured on the grey-scale images obtained using WinDENDRO software v. 2014 (Regents Instruments Inc.). Visual cross-dating of core A and B was carried out with the software CDendro (v. 7.7, CybisElectronik and Data AB) and verified statistically using the dplR-package (Bunn 2008) of the R programming software v. 3.1.1 (R Foundation for Statistical Computing). The same package was used to detrendthe series with a modified negative exponential curve or straight line to eliminate age trends. Standard chronologies of each microsite were built applying a biweight robust mean.

*Climate data*

Temperature and precipitation data were obtained from the CRU TS 3.22 0.5°x0.5° gridded dataset for the period 1901–2013 (Harris et al. 2014). Based on these data, mean annual temperature and annual precipitation are–2.5°C and 509mm in Kenesjärvi, and –1.5°Cand 442 mm in Laanila, respectively. At both locations, July is the warmest and wettest month (12.3°C/69 mm in Kenesjärviand 13.6°C/70mm in Laanila, respectively). Calculating a 30-years running mean (1 year lag) for July mean temperature and July precipitation sums identifies the coldest (1942–1971) as well as the warmest phase(1913–1942) of the observed period for both Kenesjärvi (lowest mean: 11.9°C, highest mean: 12.8°C) and Laanila (lowest mean: 13.3°C, highest mean: 14.1°C)(Fig. 1). The beginning of the 20[th]century(1921–1950 for Kenesjärvi and 1901–1930 for Laanila) comprises the driest years for July(55 mm/62 mm),
While July precipitation has been clearly increasing over the past decades (mean of 78 mm in 1982–2011 in Kenesjärvi and in 1984–2013 in Laanila).
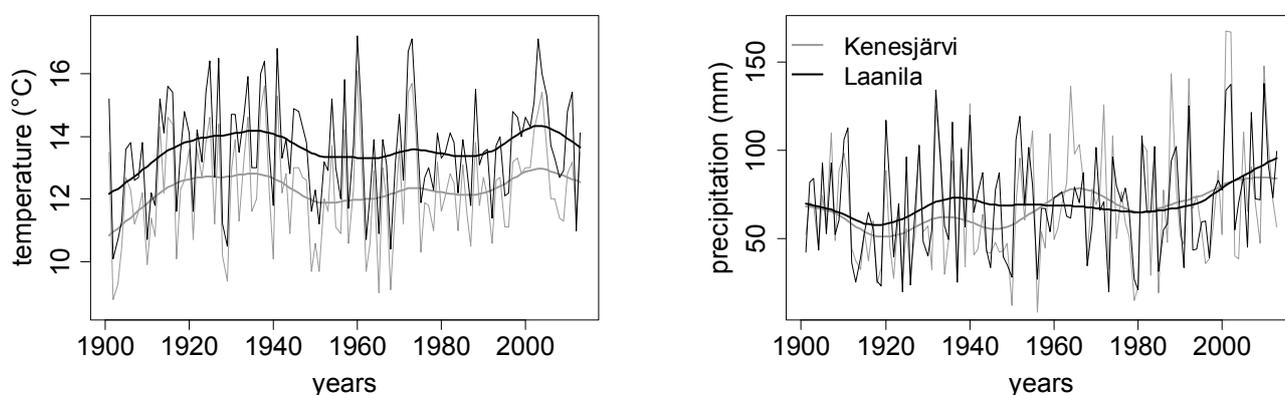


*Figure 1: July mean temperature (left) and July precipitation sums (right) for the period 1901–2013 according to the CRU TS 3.22 dataset. Smoothed curves highlight long-term trends.*

*Statistical analysis*

To calculate climate–growth relationships for each microsite, standard chronologies were correlated with monthly mean temperature and monthly precipitation sums of the period 1901–2013, including all months from June of the year prior to growth up to September of the current year. To test the stability of the climate–growth correlations, a moving window analysis was performedfor the relevant months (May to August of the current year) over the same period with a step-size of one year and a windows length of 25 years. All climate–growth analyses were carried out using the R-package treeclim (Zang& Biondi 2015), applying stationary bootstrapping in static and moving correlation functions. Confidence interval was set to 95%.

## Results

*Growth performance*

Age did not differ significantly between dry and wet microsites in Kenesjärvi or Laanilawhile growth did (Table 1): On average, trees on dry sitesare taller and have a larger crown in both northern and southern sites. In Laanila, trees differ significantly also in breast-height diameter (dbh) and average growth rateamong the two microsites. Overall, trees from Laanila are notably older and taller than trees from Kenesjärvi, while their average growth rate is smaller. Trees from Laanilawet site (LW) are the smallest in average growth rate, dbh, crown area and crown volume.

*Table 1: Selected metadata (mean values) for all microsites. Crown area and volume were calculated based on formulas for a circle (the mean of two radii perpendicular to each other was used) and a cone, respectively.Significant differences among wet and drymicrosites within one location are marked with an asterisk (p<0.05). Site abbreviations: K = Kenesjärvi; L = Laanila; D = dry; W = wet.*

| site | ø age | ø growth rate (mm) | dbh (cm) | height (m) | crown base height (m) | crown area (m²) | crown volume (m³) |
|------|-------|--------------------|----------|------------|----------------------|------------------|--------------------|
| KD | 190 | 0.91 | 41.2 | 13.3* | 2.3 | 38.7* | 147.0* |
| KW | 192 | 0.84 | 38.5 | 11.4* | 2.0 | 31.3* | 98.3* |
| LD | 302 | 0.70* | 49.6* | 21.1* | 3.5 | 40.7* | 240.8* |
| LW | 261 | 0.57* | 34.8* | 13.2* | 3.3 | 23.0* | 86.6* |

As climate data is available only from 1901 on, we concentrate on the 20th and beginning of the21[st] century for radial growth. Site chronologies are well replicated back to 1840 though (at least 15 trees are available for each microsite), which is reflected in high values of glk, rbar and EPS (clearly above 0.85 in the period investigated, Tab. 2) and thus emphasizes the strong common signal of trees per microsite (Wigley et al. 1984).

*Table 2: Standard-chronology statistics. Site abbreviations: see Table 1.*

| site | n | period | glk | rbar | EPS <0.85 before |
|------|---|--------|-----|------|------------------|
| KD | 26 | 1779–2014 | 0.72 | 0.52 | - |
| KW | 19 | 1751–2014 | 0.72 | 0.52 | 1814 |
| LD | 20 | 1547–2014 | 0.68 | 0.41 | 1714 |
| LW | 17 | 1545–2014 | 0.68 | 0.50 | 1789 |

Overall, trees from all microsites show similar relative growth ratessince the beginning 20th century (Figure 2): A period of reduced growth during the first 10–15 years of the 20th century is followed

by a phase of enhanced growth until around 1940. Since that time, growth rates first decreased until about 1960 and then remained more or less stable until today.At high frequency, slight differences in various periods become apparent between the microsites:

Trees grow better in wet than in dry sites in the period 1940–1950. Recently,growth performance splits up between northern and southern sites: Trees from Laanila grow better than trees from Kenesjärvi from the late 1970s until the early 1990s, while this relation inverses since around 2000.
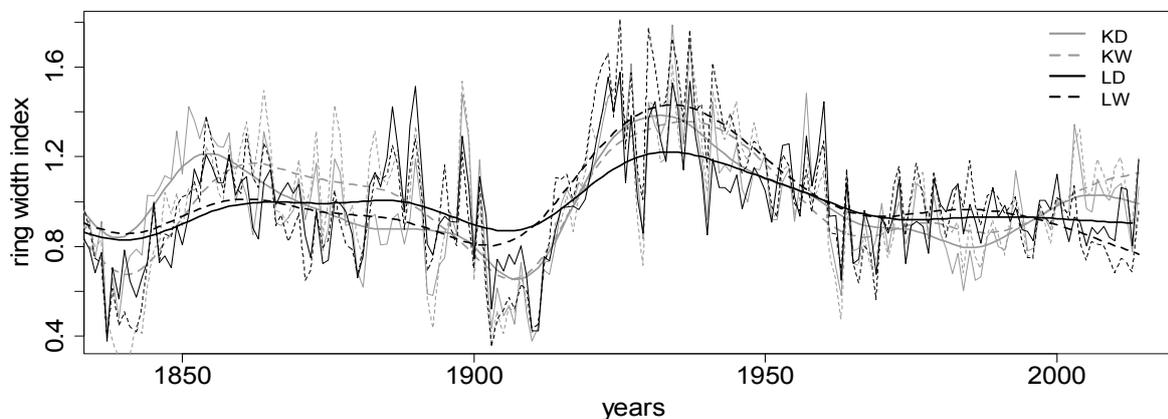


*Figure 2: Standard chronologiesof all microsites. The series are truncated at 1840 (sample depth falls below 15 in KW and LW beyond this point). Smoothed curves highlight long-term trends.*

### Climate–growth relationships

Tree-ring width(TRW) in all sites shows a strongly significant ($p<0.05$) positive correlation with July temperature and a weaker negative correlation with July precipitation of the current year (July temperature, KD: r=0.48, KW:r=0.50, LD: r=0.44; LW: r=0.42; July precipitation, KD: r= –0.23, KW: r= –0.25, LD: r= –0.16, LW:r= –0.17). Other significant correlations exist between TRW and August temperature (KD: r=0.34, KW: r=0.31, LD: r=0.19) and precipitation in May of the current year (KD: r=0.16, KW: r=0.21, LD: r=0.25). All sites except LW are significantly positively correlated with previous year's summer and autumn temperatures, but these are not further examined here.

The stability test showed correlations with July temperature being more or less stable for both microsites of Kenesjärvi, but not of Laanila (Figure 3): Since the 1980s, the strength of July temperature correlations is decreasing continuously and is turning insignificant recently. July precipitation starts to lose its negative influence clearly in the middle of the century in both Kenesjärvi sites, while at the same time May precipitation becomes a significant positive influence. In LD, however, May precipitation has become less influential recently.

## Discussion

### Growth performance

The generally better tree growth (average growth rates, dbh, height, crown volume) on dry microsites is most likely due to site differences, as age was excluded as the driving factor (no significant difference in age between microsites). This is in line with findings of previous studies (Düthorn et al. 2013, 2015, Helama et al. 2013). The lower dbh, height and crown values of Kenesjärvi trees in comparison to LD trees can likely be explained by their younger age and the latitudinal differencewith lower temperatures and shorter growing season in the northern location. LW site trees show reduced growth in almost all parameters even when compared to KW site trees, possibly due to excess water stress. This results in colder soils with decreased root functioning, thus hampering tree growth at the lakeshore to a certain extent, similarly to what has been reported for Scots pine by e.g. Linderholm et al. (2002), Moir et al. (2011), and Helama et al. (2013).
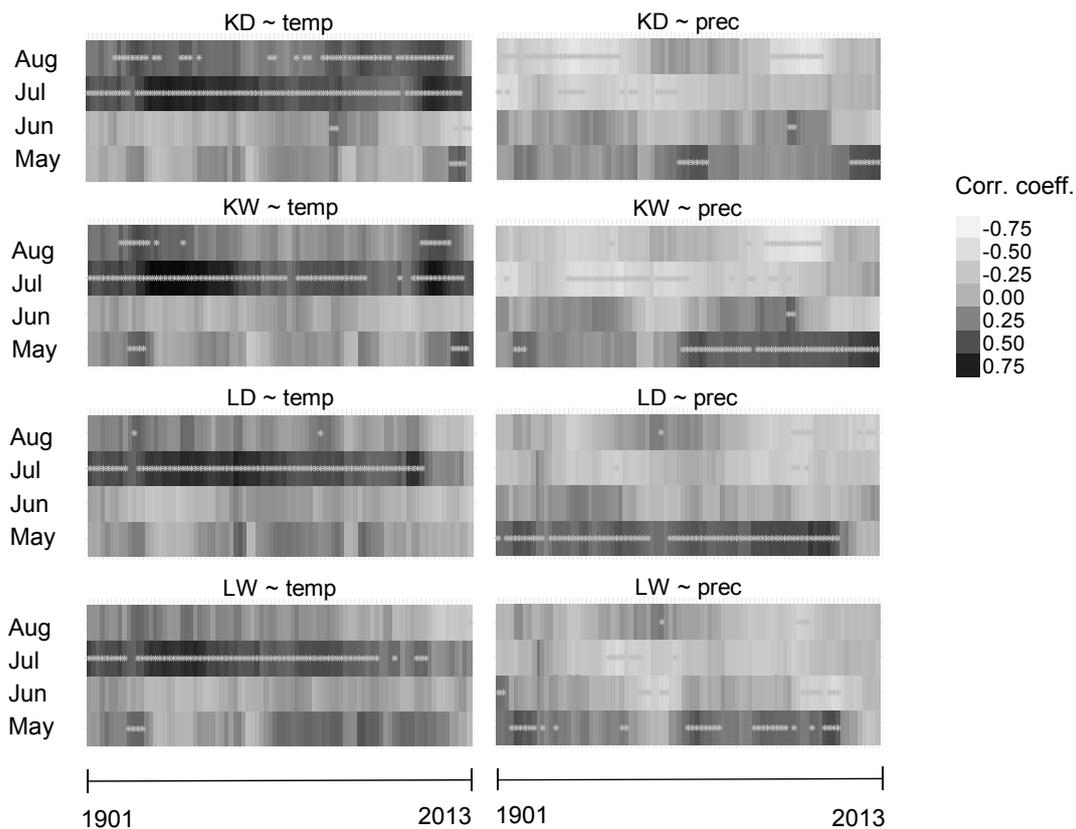
*Figure 3: Moving window climate–growth relationships (windows length: 25 years, step-size: 1 year) for all microsites with mean monthly temperature (left) and precipitation sums (right), respectively. White colouring indicates negative, black colouring positive correlation. Grey asterisk indicates that the correlation is significant (p<0.05).*

The congruent long-term growth trend of all chronologies, showing reduced growth in the beginning 20th century and enhanced growth in the decades thereafter clearly reflects the dominant climatic conditions of the larger area, which has also been reported from other studies in Fennoscandia (e.g. Tuovinen 2005, Büntgen et al. 2011, McCarroll et al. 2013, Lindholm et al. 2014, Düthorn et al. 2015).

*Climate–growth relationships*

All sites reflect the same temperature (positive with July) and precipitation (negative with July) signalsof the current year. In terms of diverging growth responsewe were thus not able to identify differences among dry and wet microsites by calculating 'common' climate–growth relationships over the entire period.Theweaker response of LW trees to climate supports the assumptionthat trees at the lakeshore areinfluenced by water table levelin addition to climate and thus the interpretation of their climate–growth relationshipsischallenging, as reportede.g. for Scots pine in Sweden (Linderholm et al. 2002)and Finland (Smiljanić et al. 2014).Overall, if the individuals investigated here were susceptible to drought conditions, we would have expected a divergent growth response to climate, namely dry site trees showing a negative response to elevated summer temperatures, as e.g. reported by Wilmking et al. (2005) and Seo et al. (2011) for certain groups of individuals, whileat the same time reacting positively to summer precipitation (e.g. D'Arrigo et al. 2008).

When focusing on the stability of climate–growth relationships over time,however, a striking difference between northern and southern locationsbecomes apparent. To make this point more evident, weplotted smoothed curves of the standard chronologies and the corresponding mean

temperature/precipitation valueson top of each other, after having performed a z-transformation of both(Fig. 4):Both Kenesjärvi chronologies follow the July temperature trend constantly (albeit at different levels), and thus seem to benefit from past and current favourable summer temperatures. In contrast, Laanila growth rates have remained at the same level since the late 1960s and LW growth rates even show a clear decreasing trend since the 1990s despite simultaneously increasing July temperature. This is supported by the findings of Seo et al. (2011) from the same Laanila area, in clearly younger trees though.

One possible explanation of this contrasting evolutionconcerning sensitivitymight be the difference intree height and crown volumethat exists between the two locations.The taller shape of LD trees presumably leads to a potentially higher evapotranspiration, yet strengthened by the fact that Laanila receives the same absolute amount of summer precipitation as Kenesjärvi, while absolute summer temperatures are higher. Hence, LD trees might begin to show signs of drought stress earlier as do trees from the north. However, if due to the factors mentionedhere reduced water supply wasgrowth limiting, according to our theory we would have expectedonly LD trees to grow worse, while LW trees still should show a stable positive temperature response.

On the other hand, the higher age of Laanila trees might be thetrigger of reduced response to July temperatures. Carrer & Urbinati (2004), e.g., found an increasing sensitivity to climatic conditions of treeline European larch (*Larix decidua* Mill.)when aged above 200 years, likely connected with hydraulic limitations. However, when Seo et al. (2011) compared tree-ring widths of clearly younger trees from Laanila and Rovaniemi (250 km south of Laanila), Laanila trees also showed divergence around 2000 and thereafter while Rovaniemi trees did not, suggesting that higher age might not be the cause for the loss of sensitivity to temperature in Laanila. A test of age cohorts is needed to assess age effects ultimately for our study.

Different growth rates might finally also arise from arecenttemperature- or moisture-induced changein soil nutrient availability as e.g. found for White spruce (*P. glauca*) in Alaska by Sullivan et al. (2015). Pollution, e.g. by nitrogen, however, does not seem to affect our study sites as this area has the lowest (and stable) values compared to the rest of Europe for the period 2005–2010 (Harmens et al. 2015).
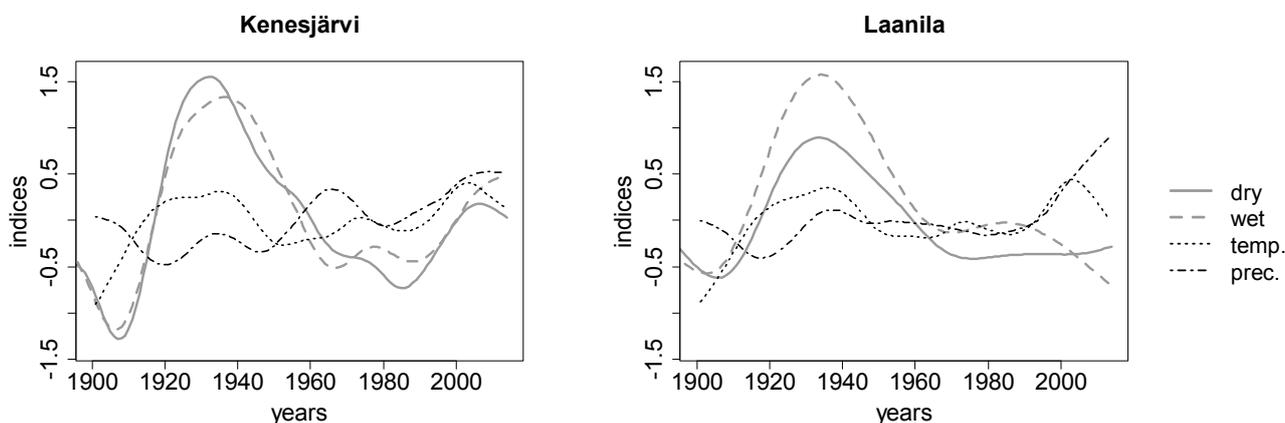


*Figure 4: Smoothed curves of the standard chronologies and the corresponding mean July temperature(left) and July precipitation sum (right) curvesfor the period 1901–2013. Both standard chronologies and climatic data were z-transformed.*

## Concluding remarks

Preliminary results suggest that differences in growth performance exist among the investigated dry, wet, northern and southern sites. When calculated over the entire period, main climate–growth correlations are similar between all microsites. But only in the northern sites, stable climate–growth correlations exist (July temperature).Our results concerning growth performance seem to be explicable throughvarying (micro-)site conditions, while the main trigger for the fading climate–

growth relationships remains unclear for now. However, these differences require further investigation (e.g. test of age cohorts), also taking into account additional environmental factors and methodological aspects (D'Arrigo et al. 2008), as well as additional tree-ring proxies (density, anatomy). These analyses are planned in the future.

**Acknowledgements**

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

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## 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.

## 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.
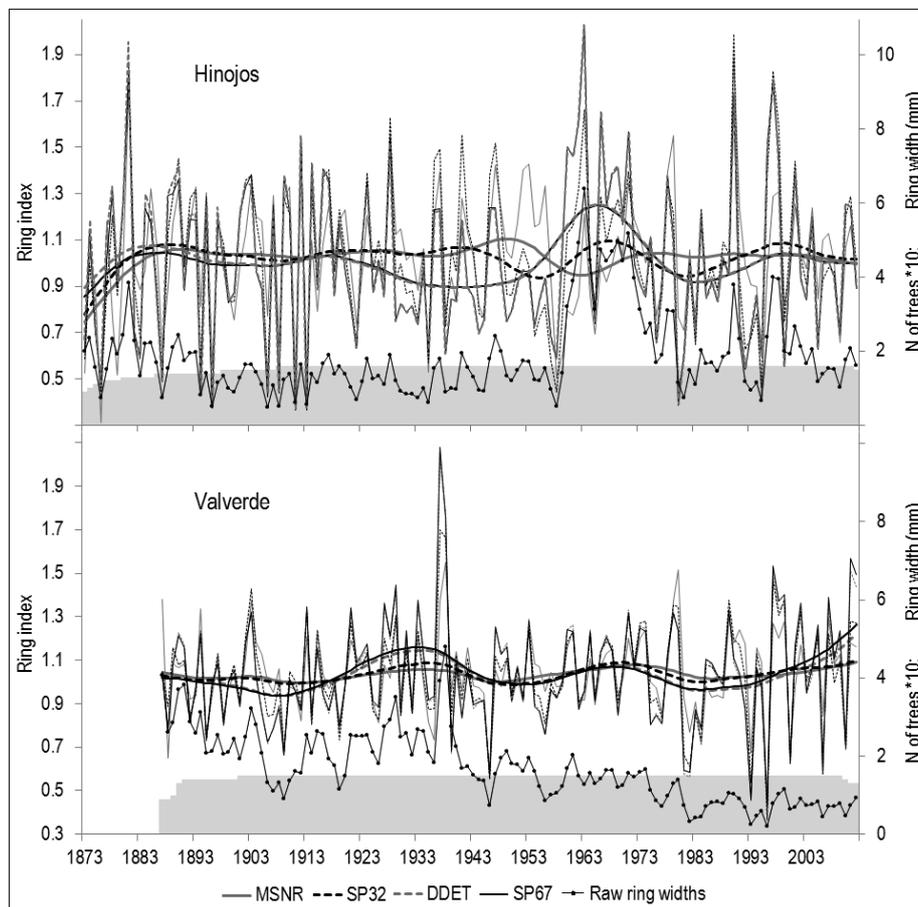


*Figure 1 Residual chronologies, mean ring-width series and sample depth*

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.
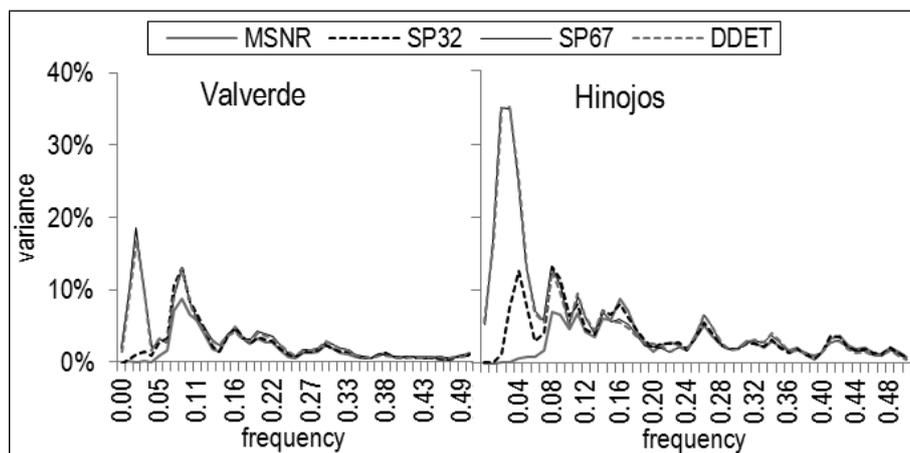


*Figure 2 Power spectra of the standard chronologies*

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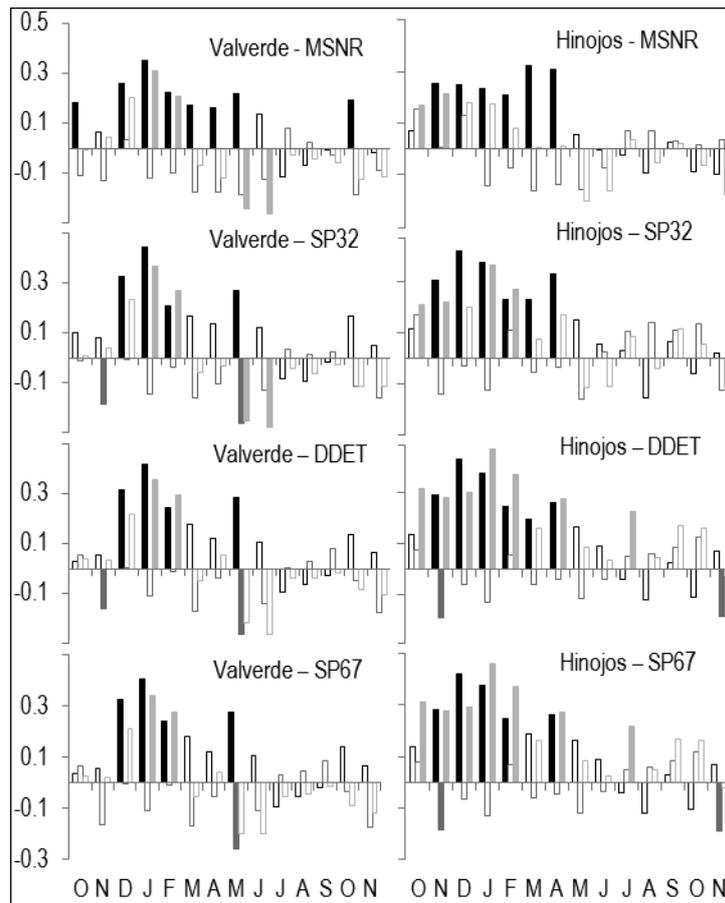
*Figure 3 Bootstrapped correlations between residual chronologies and monthly values of climatic covariates from the previous October to the current November (precipitation, maximum temperature and minimum temperatures: first, second and third bar, respectively). Filled bars indicate statistically significant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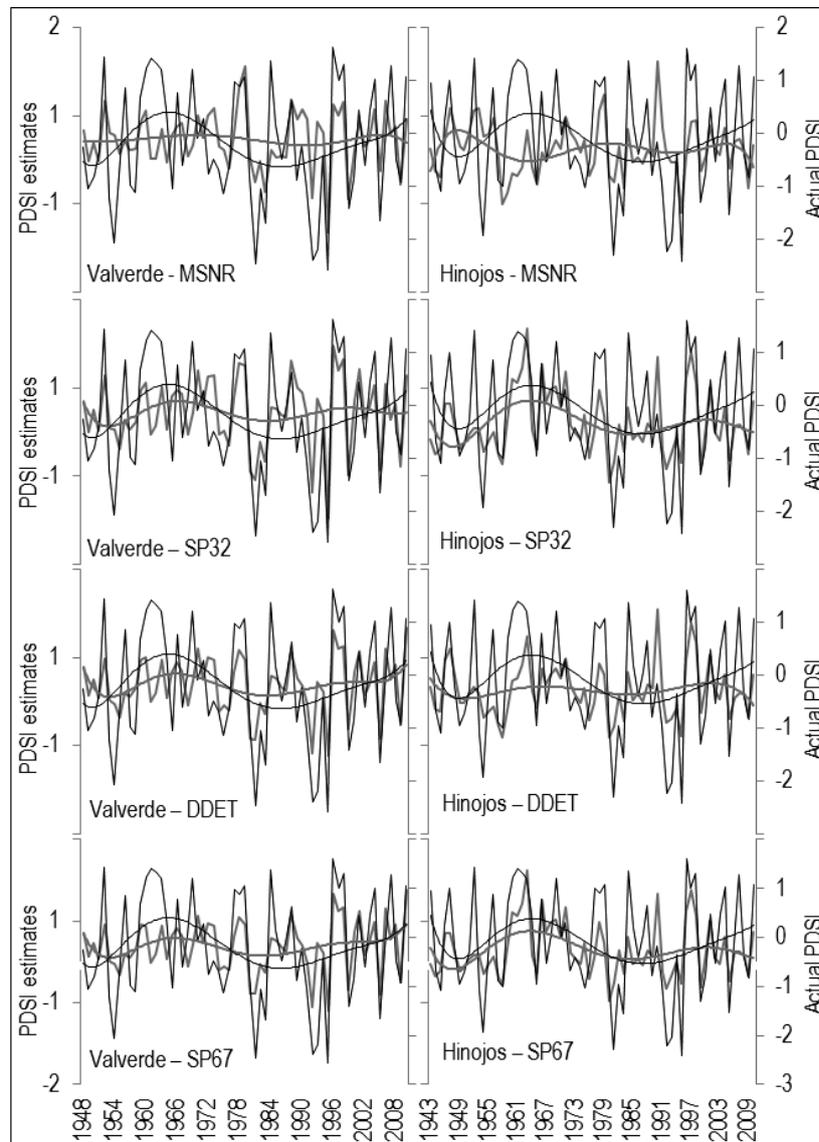


*Figure 4 Climate reconstructions. Black lines are the actual PDSI values of the indipendent period; grey lines are the climate values estimated from the residual chronologies. The fitted curves are 6th-degree polynomials.*

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# Thinning modulates climate-growth responses of *Pinus halepensis* Mill. under semiarid Mediterranean conditions

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## Introduction

According to climate predictions a rise in temperature and related aridification trends is expected in the Mediterranean area within the current century (IPCC 2014). This climate warming and higher atmospheric $CO_2$ threaten the Mediterranean forests (Lindner et al. 2010). The southernmost European planted pine forests are considered vulnerable areas to these environmental alterations (Sánchez-Salguero et al. 2012a,b). Extensive pine afforestations are highly relevant in the Mediterranean Basin from both ecological and socioeconomic points of view. This is specifically true in Spain, where ca. 3.5 million ha were reforested since the 1940s (Montero 1997). In addition, drought stress is probably among the main drivers of the current forest decline of these conifer woodlands in southern Europe (Allen et al. 2010; Sarris et al. 2010; Sánchez-Salguero et al. 2013). Drought effects on tree growth and performance can be aggravated in densely-stocked stands, since trees suffer from a long-term stress by sustained intense competition, which results in higher sensitivity to short-term stresses such as severe drought events (Linares et al. 2010). Forest managers use thinning to reduce tree competition for water within stands (Martín-Benito et al. 2010; Del Campo et al. 2014). When properly used, thinning reduces long-term stress by competition, but it also reduces the vulnerability and increase resilience and resistance of trees to extreme drought events (Linares et al. 2011; Sánchez-Salguero et al. 2013). Radial growth responses to climate considerably vary according to local tree density and crown class in areas where water is limiting (Martín-Benito et al. 2008; Linares et al. 2009). In general, a reduction of drought sensitivity usually results from thinning practices, but without increasing the intrinsic water use efficiency (Martín-Benito et al. 2010), which can be interpreted as a reduced competition for the available water after thinning. Adaptive managements could improve growing conditions, and therefore alleviate water stress that constrains photosynthetic activity and tree growth (McDowell et al. 2003).

In the present study, we aimed to contribute on the knowledge about the importance of adaptive management in the Mediterranean afforestations. To do so, we selected Aleppo pine (*Pinus halepensis* Mill.) as our study system. This species is the most widely distributed pine species throughout the Mediterranean Basin and one of the best adapted tree species to drought (Pausas 2004). Aleppo pine is subjected to frequent summer droughts (De Luis et al. 2007) and it is one of the Mediterranean forest species most used in reforestation programmes, especially in semi-arid areas of the Iberian Peninsula (Montero 1997). The adaptation of Aleppo pine to these Mediterranean climate conditions is determined by its resistance to water-stress in long periods of droughts as well as its recovery capacity after drought occurrence. For this study, we used dendrochronological methods over afforested stands of managed *Pinus halepensis* in the Mediterranean area. The main objectives were *i)* to assess the growth reactions to thinning on tree growth and *ii)* to evaluate the effects of thinning on climate-growth responses and drought sensitivity.

## Material and Methods

### Study design and sampling

Our study area was located in the "Cortijo del Conejo-Albarrán" in Granada province, southern Spain (37° 26´N, 03° 5'W) at an altitude of 1115 m a.s.l. (Fig. 1). The study area was a tilled agricultural zone until 1993 when the land was acquired by the Regional Government of Andalusian. Trees are in a pure *P. halepensis* stand (afforestation of 1200 ha) established in a degraded agricultural land during 1994-1995 at an initial stand density of 1500 trees ha$^{-1}$. The mean annual rainfall (1996-2013 period) is 320 mm and the temperature can range from -15 °C in winter to exceed 40°C in summer. These values correspond to Mediterranean continental arid conditions. The soil is petric calcisol (FAO-ISRIC 1998) and homogeneous throughout the assay area. The study area was subjected to four thinning treatments in January 2005, and four final densities were defined according to the basal area removed: T-75 (75% of basal area removed), T-60 (60%), T-48 (48%) and control T-0 (0%) (Tab.1). Each thinning treatment was composed by four monitoring plots.
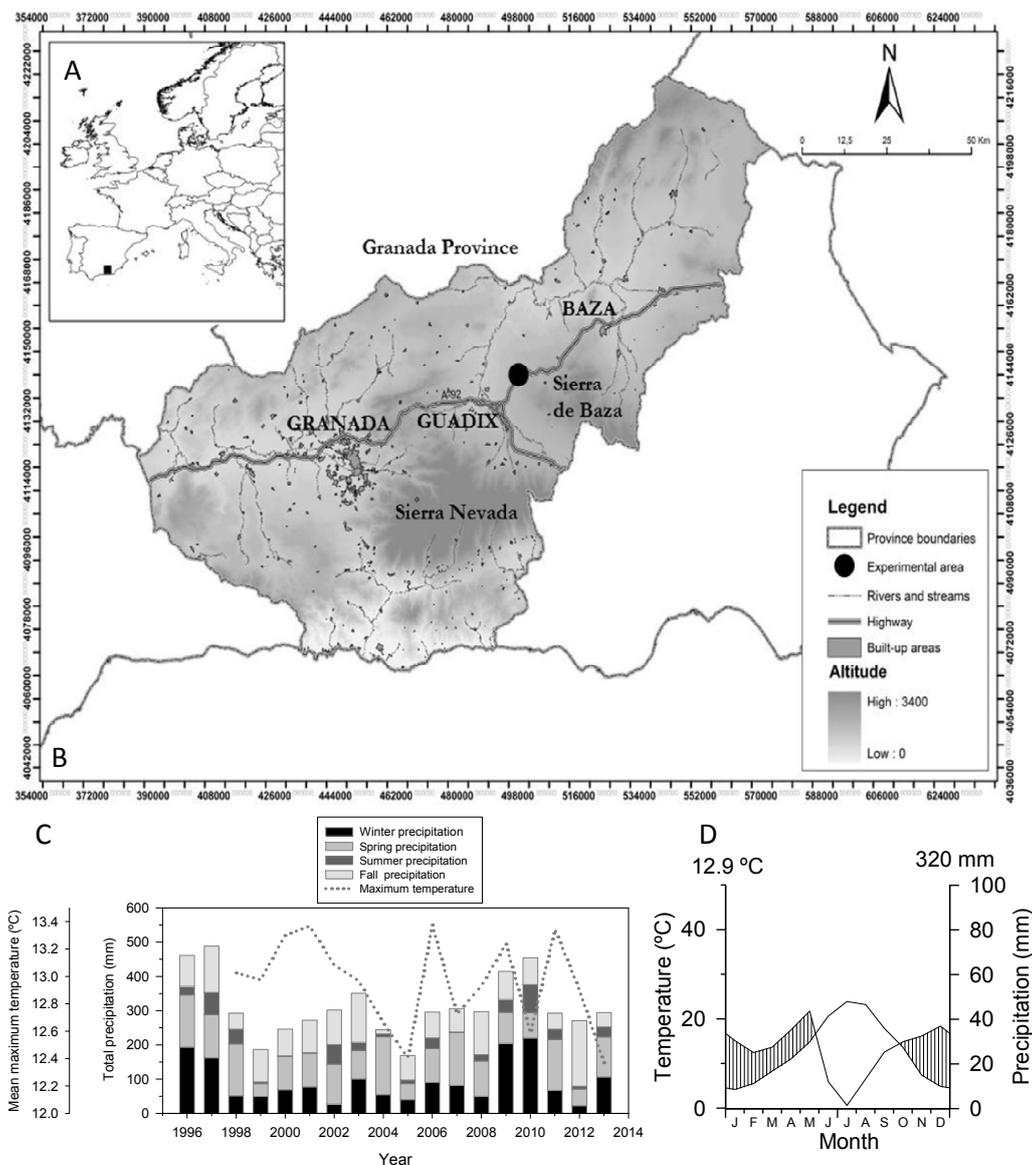


*Figure 1: A) Location of the study area in the Andalusian region, southern Spain. B) Location of the study plots in the province of Granada. C) Trends in mean maximum temperature and seasonal precipitation in the study area in the period 1996-2013. (data from own climatic station located in the area and the Spanish National Meteorological Agency) D) Climate diagram of the study area.*

Dendrochronological sampling was conducted during spring 2013. In each thinning plot at least 30 trees were cored at 1.3 m with a Pressler increment borer and four cores were sampled per tree along the direction perpendicular to the maximum slope. Cores were air dried, sanded until tree-rings were clearly visible and then the cores were visually cross dated (Yamaguchi 1991). Individual tree-ring width series were measured to the nearest 0.01 mm with a LINTAB measuring device (Rinn 2003). Cross-dating quality was checked using the software COFECHA (Holmes 1983) by checking the consistency of the different ring-width series among trees coexisting within the same plots. We assessed chronology quality from the common signal among trees using the mean correlation between trees (IC), the expressed population signal (EPS), and the first-order autocorrelation (AC), whereas mean sensitivity (MS) served as a measure of year-to-year variability (Briffa & Jones 1990). To analyze changes in growth patterns, we calculated annual basal area increment (BAI) using the following equation: $BAI = \pi(R^2_t - R^2_{t-1})$ where R is the radius of the tree and $t$ is the year of tree-ring formation (Biondi & Qaedan 2008).

*Thinning effects on climate-growth responses and drought sensitivity*

Thinning effects on growth-climate relationships were quantified using Spearman correlation coefficients. Mean BAI for each treatment and monthly climatic series were compared before and after thinning from August of the year prior growth to September of the year of growth since this is the most influential period for radial growth of the studied species (De Luis et al. 2007, Camarero et al. 2010). We also studied the long-term responses of BAI to thinning using the percentage growth change (GC) filter (Pérez-de-Lis et al. 2011). This method is a powerful technique for the identification of release events in tree-ring series based on the fact that trees surviving after thinning respond with a released growth (Copenheaver & Abrams 2003). Individual GC chronologies were calculated from BAI series by applying the formula: $GC = [(BAI_{post} - BAI_{pre}) / BAI_{pre}] \times 100$, where $BAI_{pre}$ and $BAI_{post}$ are the preceding and subsequent seven-year mean BAI. To estimate the thinning effects on tree growth response to drought (DS) we quantified the relative mean reduction in BAI as related to 2009 severe drought. We calculated the percent BAI reduction as follows: $DS = 100((BAI_t - BAI_{t-1})/(BAI_t + BAI_{t-1}))/2$ where $BAI_t$ and $BAI_{t-1}$ are the BAI values for the drought year ($t$) and the previous one ($t-1$), respectively. In all cases $BAI_t$ was lower than $BAI_{t-1}$. In order to characterize the effects of thinning treatments on the growth recovery after drought we calculated drought recovery index (DR) following this equation: $DR = ((BAI_{t+1} + BAI_{t+2})/2)/BAI_t$ (Sánchez-Salguero et al. 2013). All the statistical analysis were performed using R package, version 3.1 (R Development Core Team 2014).

**Results and Discussion**

*Climate trends and growth patterns*

In the study area we observed that a significant ($P < 0.05$) increase in maximum temperatures and opposite trends in the growing season precipitation promoted an increased drought stress. Therefore, growth was mainly favored in years exhibiting wet and mild springs and summers (Figure 2) as has been reported by Sánchez-Salguero et al. (2010). The BAI time series per treatment showed similar patterns of temporal evolution, but different growth recoveries among treatments under extreme events, i.e., droughts. All treatments exhibited a bimodal evolution of growth values, presenting two maximum growth peaks at 2006 and 2011, and a sharp reduction in the 2009 drought (Fig. 2). Despite of this variation in growth differences, our data shows that the differences in BAI among thinning treatments decrease under drought stress consistent with findings of previous studies (e.g. Martín-Benito et al. 2010). In this sense, trees in unthinned plots (control treatment, T-0) presented lower growth rate than those in thinned areas (T-60 and T-75), and dbh and BAI decreased as thinning intensity increased (Fig. 2, Table 1). This suggests that thinning treatments mitigate the negative drought effects on tree growth. This is in line with Martín-Benito et al. (2010) and Nunes et al. (2014). After treatment, dbh exhibited significantly lower

values for the treatment with higher density of trees (T-0), while lower stand density showed significantly higher values (T-60 and T-75, respectively). These findings are also supported by BAI trends (Table 1).

*Table 1: Stand characteristics before thinning treatments (pre) and eight years after (post). Diameter measured at breast height: dbh. BAI: Basal area increment. Values are means ± SE. Different letters indicate significant (P< 0.05) differences in the same plot before/after thinning (lowercase) and between treatments (capital) (Mann-Whitney U test).*

| *Treatment* | *Post-thinning Density (tree ha$^{-1}$)* | *dbh (cm)* | | *BAI (cm$^2$ year$^1$)* | |
|---|---|---|---|---|---|
| | | *pre* | *post* | *pre* | *post* |
| *T-75* | *325* | *5.5±0.3a* | *12.1±3.29bA* | *15.3±8.8b* | *11.5±4.3aA* |
| *T-60* | *513* | *5.4±0.2a* | *11.9±2.82bA* | *13.1±7.9b* | *9.2±4.7aB* |
| *T-48* | *618* | *5.3±0.2a* | *10.6±3.13bB* | *11.7±6.7b* | *6.3±4.1aC* |
| *T-0* | *1444* | *5.1±0.1a* | *8.9±2.8bC* | *8.5±5.6b* | *3.7±3.2aD* |

These results confirm the well known negative impact of water and light stress on tree growth (Valladares & Pearcy 2002). By reducing stand density, inter-specific competition for limiting resources is diminished (Linares et al. 2010). For example, belowground competition for water or nutrient is mitigated when tree density is reduced as previous studies showed (Blanco et al. 2005, Del Campo et al. 2014). Increased growth rates by heavy thinning are usually linked to the simultaneous enhancement of tree water status and illumination within the stand as inter-tree competition is reduced (Aussenac 2000). A higher water supply allows a higher stomatal conductance and carbon assimilation, which improve tree growth (McDowell et al. 2003), and extend the growing season (Linares et al. 2009, Sánchez-Salguero et al. 2015).
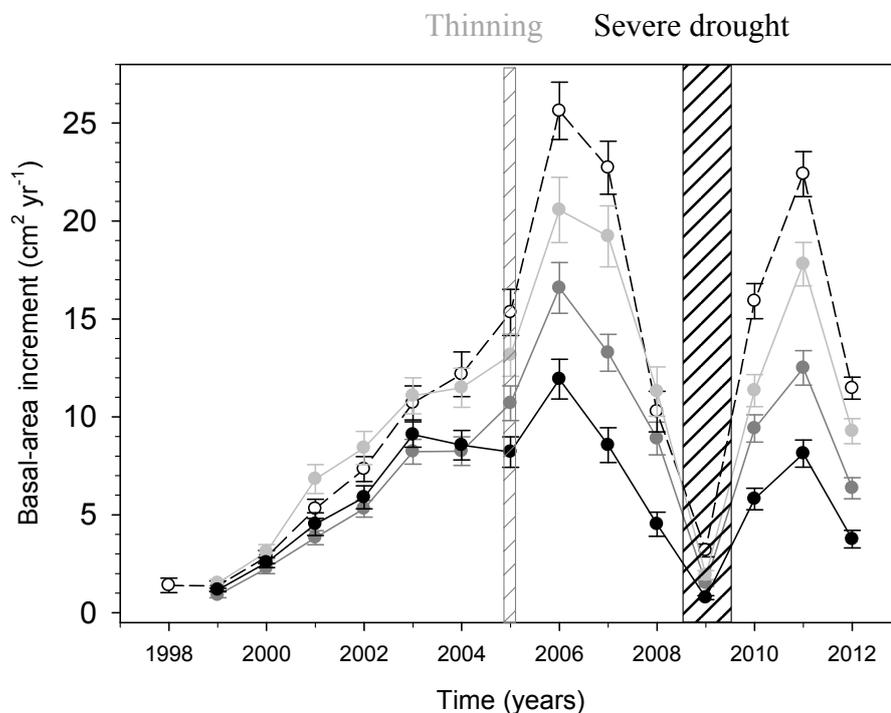


*Figure 2: Recent trends in basal area increment (BAI) for each treatment: T-75 (white), T-60 (dark grey), T-48 (light grey) and control T-0 (black). The solid vertical lines indicate the date of thinning in 2005 and the severe drought event in 2009.*

*Climate-growth responses*

Our results showed that thinning treatments modulated the growth-climate responses such as Pérez-de-Lis et al. (2011). During the whole period, April precipitation was positively related to growth, whereas June precipitation was significant and positively related to growth only after thinning (Fig. 3), higher in T-0 than in thinned plots caused by competition effects. Tree growth after thinning was enhanced by wet conditions in January. On the other hand, the lower density thinning treatment (T-75) did not present the significance effects found for the other treatments for the previous autumn precipitation, whereas the previous autumn negative effects of temperature increased after thinning (Fig. 3). Warm conditions in May also negatively influence growth of high density stands (Pasho et al. 2011). These results indicate that at low density, trees respond faster to late-winter precipitations and therefore expanding their growth period (Camarero et al. 2010) (Fig. 3).
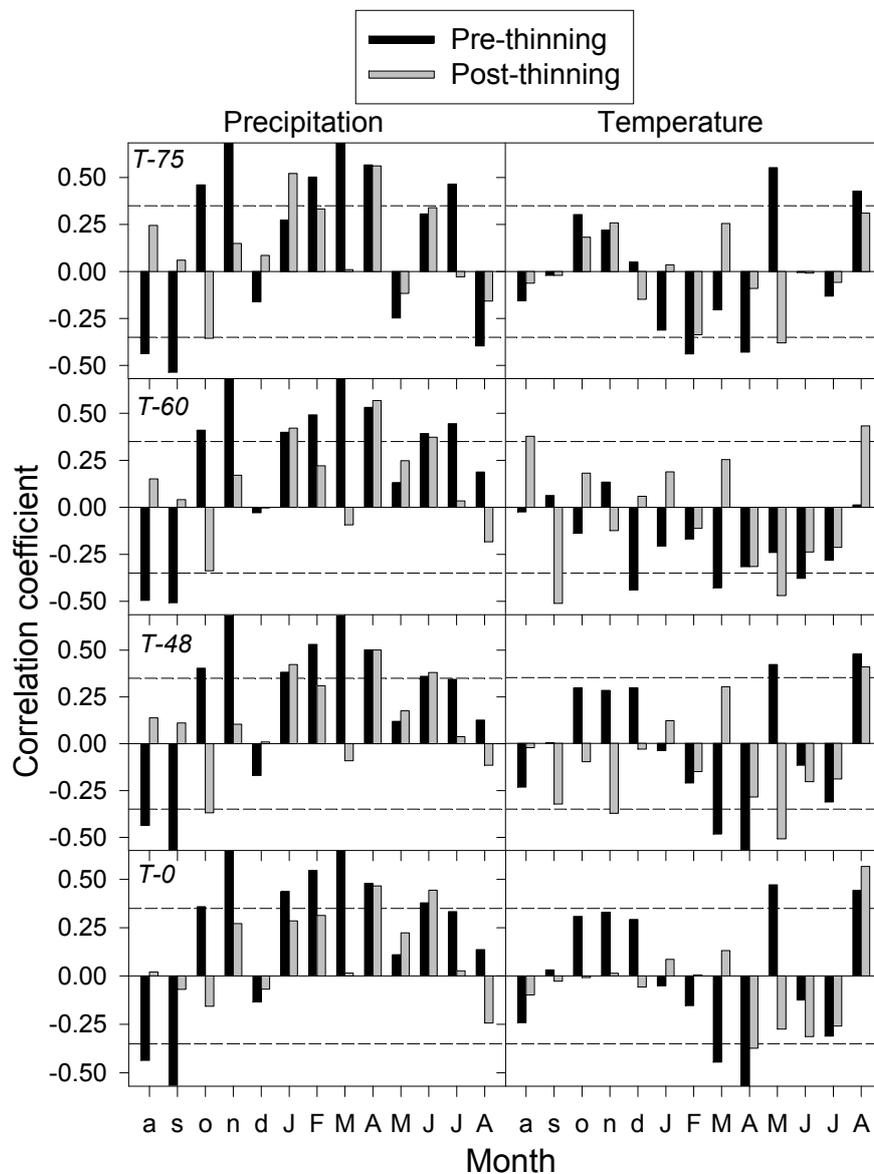


*Figure 3. Spearman correlations between radial growth (BAI) and monthly climatic variables in the pre-treatment (1996-2004) and post-treatment (2006-2013) periods. Tree growth is related with climate data from the previous (months abbreviated by lowercase letters) and current (months abbreviated by uppercase letters) years, being the current year that of tree-ring formation. The significance levels (P < 0.05) are indicated by dashed horizontal lines.*

*Thinning effects on growth resilience to drought*

The first-order autocorrelation (AC) of the tree-ring width individual series was higher in high density plots than in heavily thinned stands, suggesting a higher year-to-year persistence in growth of the control plots, whereas the mean sensitivity (MS) was lower in T-75 than in control stands indicating a higher inter-annual variability of radial growth in the unthinned stands (Table 2). The mean correlation between trees (IC) and the expressed population signal (EPS) were higher in dense stands than in heavy thinned stands.

The selected dry year (2009) after thinning coincided with sharp reductions in BAI in all the plots (Fig. 2). The maximum reduction in growth was detected for trees from high density stands (T-0 and T-48) in response to the 2009 drought, being significantly lower in heavy thinned plots (Table 2). Moreover, thinning enhanced BAI in favorable years and improved the recovering of tree growth after droughts or other disturbances (Alfaro-Sánchez et al. 2014).

The mean relative BAI reduction in response to 2009 drought (DS) was significantly higher ($P < =0.05$) in high density plot (T-0) than in the rest of stands (Table 2). The minimum DS was detected for the T-75 stands, suggesting that drought impacts and resilience in planted Aleppo pine are modified by thinning intensity (Del Campo et al. 2014). Furthermore, drought recovery (DR) was significantly higher in T-75 and T-60 than in the lightly thinned plots (T-48 and T-0). As a result, heavy thinned stands were more resilient than lower thinned or control stands (Table 2) (Sánchez-Salguero et al. 2013). Our results are in accordance to previous studies, which reported poor individual tree growth responses after light thinning in comparison to heavy thinning (Cañellas et al. 2004; Martín-Benito et al. 2010). We showed that thinning favours tree growth and provides more resilience to extreme drought events. Similar results were found for trees suffering from different intensities of competition, or as a result of thinning experiences, either under Mediterranean (Linares et al. 2009; Martín-Benito et al. 2008) or temperate climates (Kohler et al. 2010).

*Table 2. Dendrochronological statistics of the radial growth series for the whole period (1996-2013); percentage growth change (GC) after thinning treatments (2005) and drought sensitivity (DS) and drought recovery (DR) in 2009. Values ± SD. Different letters indicate significant (P< 0.05) differences (Mann-Whitney U test).*

| Treatment | IC | AC | MS | EPS | GC | DS | DR |
|-----------|------|------|------|------|-----|-----|-----|
| T-75 | 0.662 | 0.432b | 0.504c | 0.98 | 180.2 ± 80.2a | 84.3 ± 50.3d | 13.1 ± 7.8a |
| T-60 | 0.594 | 0.492b | 0.525b | 0.98 | 103.7 ± 47.4b | 100.4 ± 45.1c | 12.6 ± 6.8a |
| T-48 | 0.735 | 0.493b | 0.530b | 0.99 | 75.8 ± 50.7c | 120.7 ± 37.9b | 10.6 ± 9.2b |
| T-0 | 0.753 | 0.658a | 0.595a | 0.99 | -11.2 ± 25.3d | 146.8 ± 45.3a | 9.1 ± 7.5c |

## Conclusions

We observed that an increase in mean maximum temperatures and decrease in precipitation during the growing period promoted a reduction in water availability and increased drought effects. Therefore, growth was mainly favoured in wet springs and summers. Heavy thinning enhanced basal area increments in favorable years and improved the recovering of tree growth after droughts. Our results showed that thinning modulate tree growth responses and provides more resilience to extreme drought events (Sánchez-Salguero et al. 2013; Madrigal-González & Zavala 2014). The active response to increasing growth has important implications for silviculture in a context of global change (D´Amato et al. 2013). These findings confirm that thinning is a useful measure against climate change in plantations of Aleppo pine and emphasizes the importance of adaptive forest management in Mediterranean semi-arid areas.

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# Dendrochronoecology of ancient wine presses in the Southern French Alps

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## Introduction

In the Southern French Alps wine growing was a common practice to an altitude of 1300 m until recent times (Blanchard 1930). This past activity is evidenced by several impressive wine presses located at high elevation. Given this issue is poorly documented by archives, ten ancient wine presses were studied by using dendrochronology in order to find out more about this original heritage. How old are these structures? Which timber species were used and were they built in several stages?
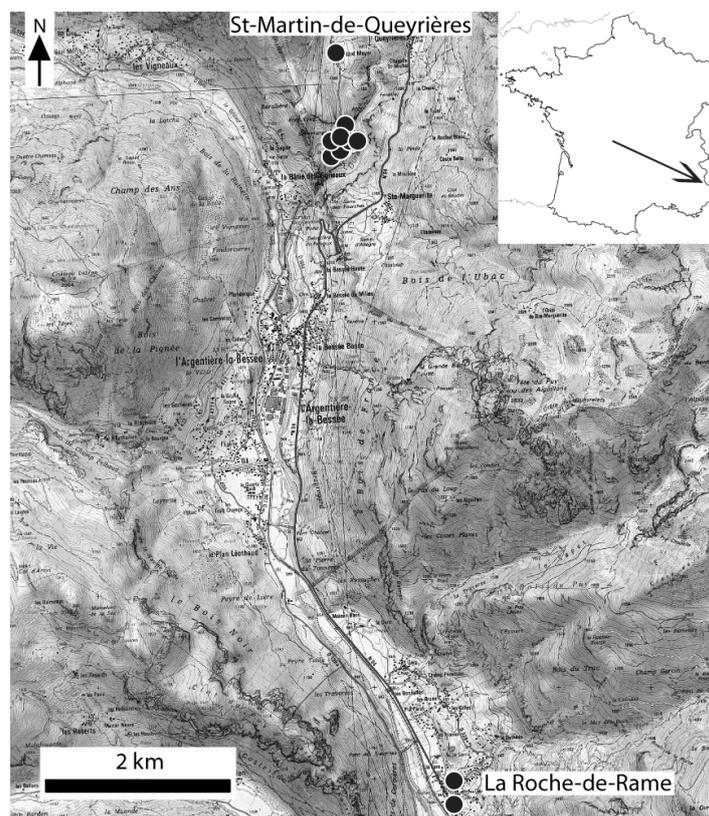


*Figure 1: Location of the studied wine presses (Background map: Geoportail.fr).*

## Presentation

*Study area*

The studied area is the upper Durance Valley, near Briançon, at an altitude of some 1100 m (Fig. 1) (WGS84 coordinates of *la Vignette* site are: latitude: 44.813331 and longitude: 6.569162). Normally, vineyards are not present at that altitude, but, thanks to the exceptional sun radiation

(due to the influence of the Mediterranean climate) on the large southern limestone slopes, the vine is potentially plentiful (Blanchard 1930).

*Latest development*

In this area, viticulture is mentioned in archives from the 12th century (Pogneau 2001) and the activity went on until the 19th century. Several factors caused the end of the Southern alpine viticulture, Phylloxera epidemic around 1890, competition with Provence wine brought with the railway and decline of agriculture activity which started *ca*. 1870 (Mouthon 2011). Nowadays, there is no more wine production and the wine presses are abandoned. A few of them are still in good condition, while others are being neglected, exposed to climatic stresses (snow, wind, drought) and thieves (Fig. 2).



*Figure 2: An abandoned wine presse at* la Vignette *site (V. Labbas).*

*The wine presses*

There are two kinds of wine press cellars: those in villages, on the lower floor of the farms, and those close to (or inside) the vineyards. However, the internal elements of the wine presses are all of the same design. They are huge devices, completely made in wood and are called "lever presses". How were they working? The grapes were dropped off into a platter and, thanks to a stone counterweigh, a lever crushed the fruits. Then the grape juice was recovered under the press (Mallé 1991). The lever, nearly as large as a tree trunk, is retained between the "twins", that is two posts placed on the counterweight opposite side. So, these wine presses were all built on two different levels: the counterweight on the first level, and, the lever and the platter on the second level (Fig. 3).
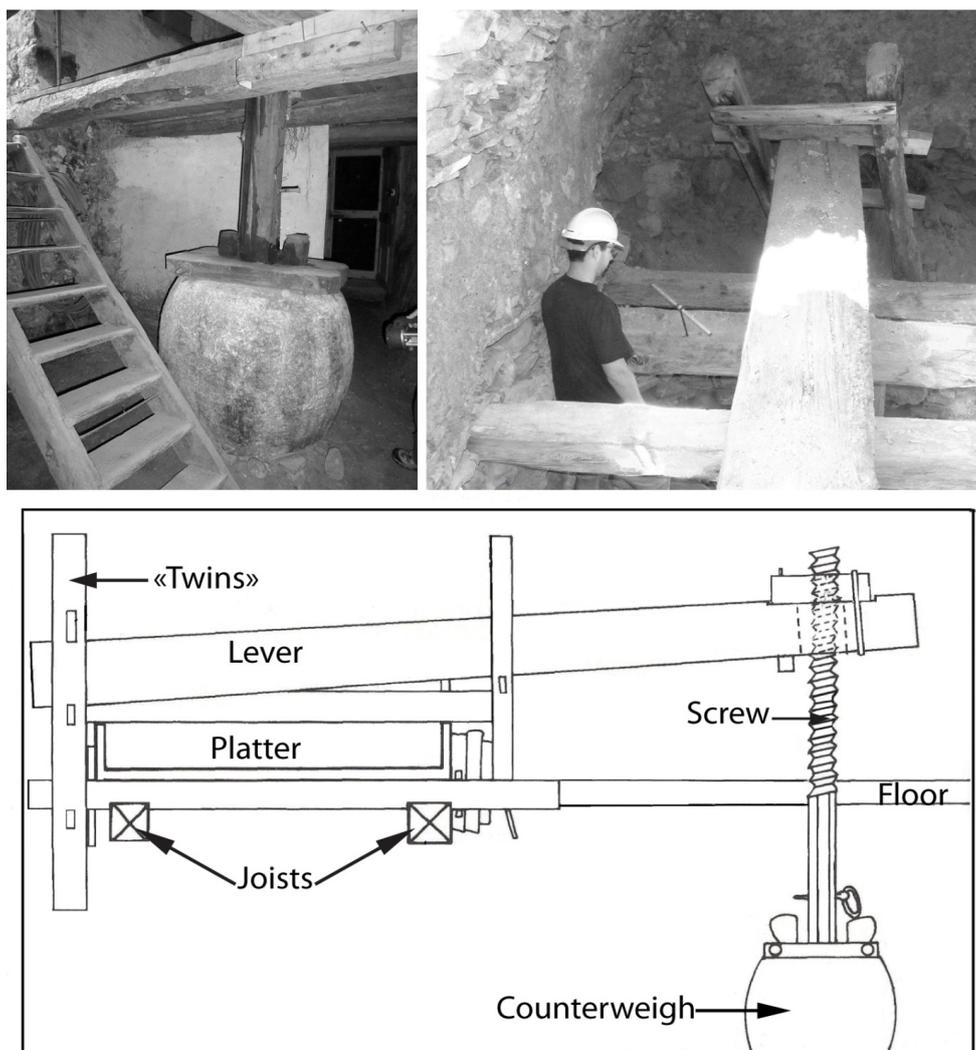
*Figure 3: Two pictures of studied wine presses and a cross-section of the device (Shindo based on Mallé 1999 p.113).*

The wine presses are located between the altitude of 970 m to 1200 m, in La Roche-de-Rame and St-Martin-de-Queyrières villages. Three of them are located in cellars of inhabited farms. The other seven are located in la Vignette site (Segard 2000) where nearly 14 hectares of vineyards were cultivated (Mallé 1999, Pogneaux 2001). In 1869, eighty cellars with wine press were mentioned, on *la Vignette* land register (Association La Vignetto, 2011) but in 2013-214 we only found seven of them in a good condition.

## Material and methods

We sampled forty-one beams with a Pressler increment borer (Haglöf, Sweden) and sometimes with an electric Rinntech driller. Function and wood species of the beams are depicted in table 1. In the lab, ring-widths were measured using the incremental measuring table LINTAB with 0.01 mm accuracy and TSAP-Win software (Rinntech Company, Heidelberg, Deutschland). Then, tree-ring series were crossdated by mean of DENDRON IV software DENDRON-IV (developed with RunRev LiveCode, Edinburgh, Scotland by G.-N. Lambert CNRS, University of Franche-Comté, Besançon, France and University of Liege, Belgium. Version: 2015 02 21).

## Results and discussion

*Wood anatomy and timber function*

Wood identification shows that larch (*Larix decidua* Mill.) is the main species (61,0%) in the wine presses. Besides that, Scots pine type (*Pinus sylvestris* L.)[1] was also used (34,1%). Initially, we thought that these wine presses were only made with larch because in mountain and subalpine vegetation stages, larch is an abundant species, commonly used in local architecture. However, Scots pine is available too in the mountain zone of this region, and even if it is less used for building, it proved to be used quite often.

Joists are mainly made in larch and levers are mainly in Scots pine. So far, sample size is too small to draw general conclusions. Nearly twenty other timbers could be sampled in la Vignette site, but because of the poor state of conservation of the structures, it is dangerous to approach them.

Scots pines used in the wine presses are larger and older than larches. Wood studies evidence that mechanical properties of larch and Scots pines are quite similar (Barnet et al. 2003). So, if the levers are mainly made in Scots pine, that would mean that large trees of this species used to be more available than larch in the surrounding forests.

*Table 1: Species and function of the sampled wood pieces.*

| Function | Larch | Scots pine | Fir | total |
|---|---|---|---|---|
| "twin" | 2 | 4 | 0 | 6 |
| lever | 2 | 7 | 0 | 9 |
| platter | 0 | 2 | 0 | 2 |
| joist | 12 | 2 | 1 | 15 |
| Various timber | 8 | 0 | 0 | 8 |
| **total** | 25 | 15 | 1 | 41 |

*Larch dating*

Sixteen of the larches beams cross-match with the southern French Alps larch master chronologies (Edouard 2010a,b, Corona et al. 2011a,b). Statistical agreement between the larch series and the master chronologies are indicated in table 2.

*Table 2: Results of the larch mean chronology synchronisation with the master chronologies. Only the best five results are presented here.*

| Date of the first ring | Date of the last ring | Covering (shared years) | Probability / security | Student t. | Rank | Master chronology |
|---|---|---|---|---|---|---|
| 1448 | 1806 | 353 | 0.999995 | 9.5 | 1 | Oriol |
| 1448 | 1806 | 272 | 0.999995 | 9.05 | 1 | MoulRef1c |
| 1448 | 1806 | 251 | 0.999995 | 8.56 | 1 | GrangesRef1 |
| 1448 | 1806 | 300 | 0.999995 | 8.4 | 1 | LachRef1 |
| 1448 | 1806 | 196 | 0.999995 | 8.34 | 1 | HipRef1 |

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[1] *Pinus sylvestris* L. and *Pinus uncinata* Ramond cannot be distinguished on the basis of their anatomic characteristics. That is why we use "Scots pine type".

*Table 3: Larches dating details and sapwood maximal estimated year (confidence level 95%).*

| Series name (larch) | First year | Last year | Sapwood ring (number) | Sapwood maximal year |
|---|---|---|---|---|
| VILL11 | 1482 | 1552 | 0 | / |
| 0515108_06 | 1448 | 1562 | 0 | / |
| 0515106_02 | 1546 | 1609 | 0 | / |
| 0515108_03 | 1526 | 1614 | 0 | / |
| 0515108_04 | 1535 | 1615 | 0 | / |
| VILL12 | 1548 | 1622 | 30 | 1642 |
| 0515108_02 | 1554 | 1627 | 16 | 1661 |
| 0515102_02 | 1557 | 1630 | 0 | / |
| 0515108_05 | 1565 | 1630 | 5 | 1675 |
| 0515108_01 | 1573 | 1633 | 5 | 1678 |
| 0515102_01 | 1533 | 1638 | 0 | / |
| 0515107_02 | 1637 | 1728 | 23 | 1755 |
| 0515103_02 | 1621 | 1784 | 23 | 1811 |
| 0515103_03 | 1666 | 1806 | 9 | 1847 |
| 0512203_02 | 1779 | 1842 | 0 | / |
| 0512203_01 | 1771 | 1854 | 13 | 1891 |

Figure 4 shows the bar diagram of the dated beams. Bark is never preserved so sapwood and/or heartwood rings may have been lost. Accordingly the exact felling date of any of these trees cannot be assessed.

Nevertheless, some of the samples have retained sapwood rings: therefore a method taking in count sapwood theoretical maximal number of ring can be applied (Baillie 1982). Therefore, a date of tree felling can be assessed.

Indeed, the study of 267 living larch from the same geographical area showed that larches they have between 14 and 50 (32 ± 18) sapwood rings (confidence level 95%) (Shindo unpublished). That made it possible to estimate the theoretical felling time interval for eight of the dated larches that still have sapwood (Table 3 and Fig. 4).

As regards samples without any sapwood rings, heartwood may have been eroded too so it is only possible to put forward a *terminus post quem*, which is a date beyond which the tree could have been felled down. That is the date of the last measured ring plus the minimal number of sapwood rings *i.e.* 14.

Accordingly, dendrochronology highlights these structures were built between the 17th and the 19th centuries. There is a major construction stage in the mid 17th century (1634-1642) and then, other construction stages in the mid 18th c. (one wood piece felled between 1729 and 1755), in the first half of the 19th century (1807-1811) and in the second half of the 19th c. (1855-1891). Timbers are not reused (no former assembly marks) so their dates correspond with their setting in the wine presses.

Dendrochronology provides detailed information on south alpine wine presses. It proves that the southern French alpine viticulture dates back at least to the 17th century, during the Little Ice Age (Grove 2003, Corona et al. 2011b). Therefore, at this time, local climatic conditions were convenient for grape maturation, in spite of the prolonged cold spell: making wine was culturally of the utmost importance, like in other areas (Pfister 1988, Le Roy Ladurie 1967, 1983).
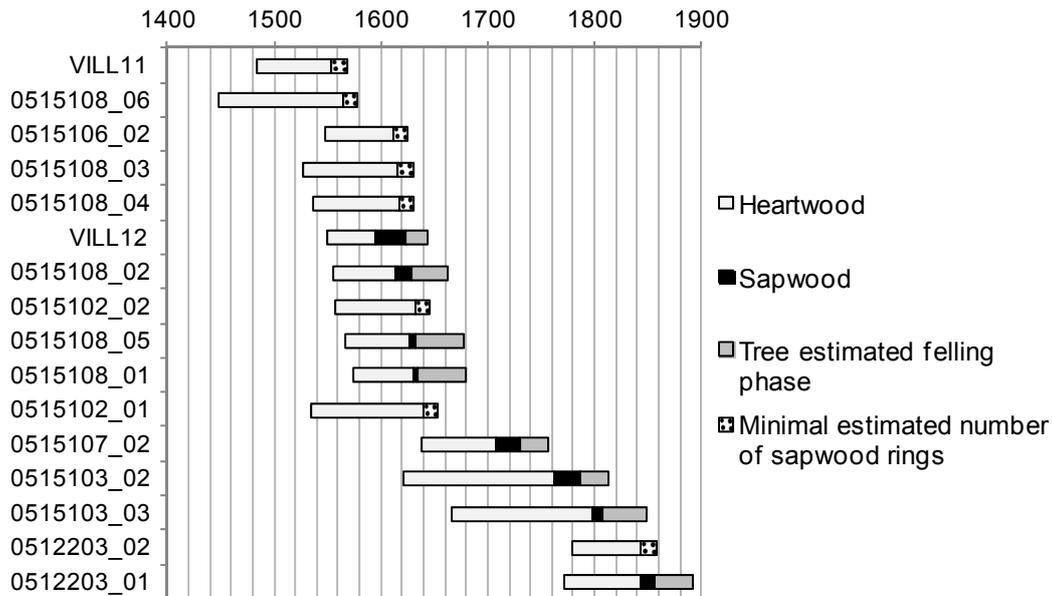
*Figure 4: Estimated felling phase of eight of the dated larches (confidence level 95%).*

## Scots pine study

A mean chronology including twelve of the fifteen Scots pines series has been developed (Fig. 5). It spans a 620-year period (ring-width series have between 71 and 334 years).
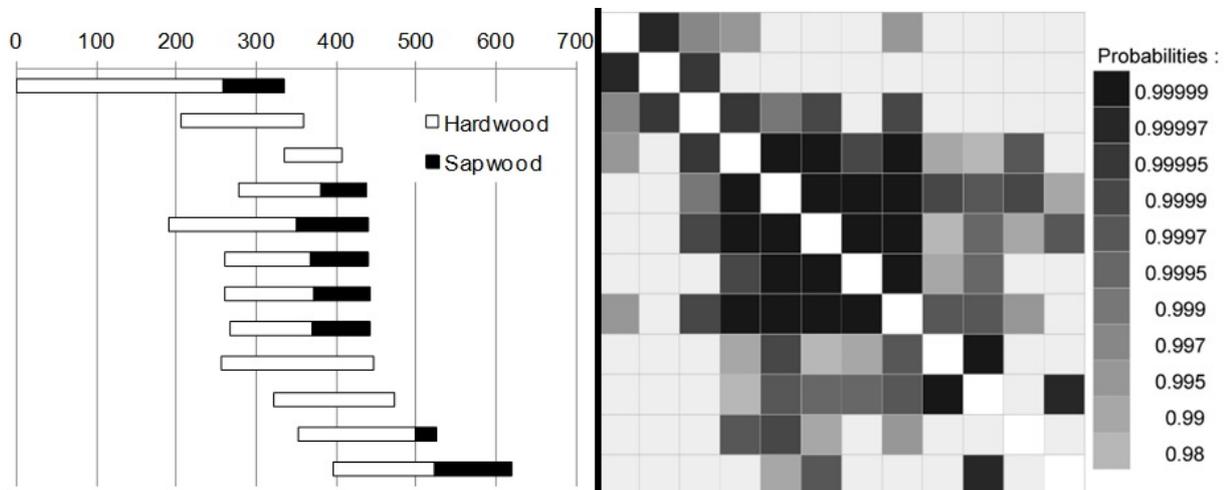


*Figure 5: Left: bar diagram of the twelve cross-matched Scots pine series. Right: Square matrix of probabilities associated with the Student t value for the twelve correlated Scots pine series (standardized by the Corridor method (Lambert 2006)). The darker is the box, the higher is the crossdating probability between the series (matrix automatically drawn by Dendron IV software Lambert 2014).*

Until now, Scots pines series could not be dated, whether it concerns the mean chronology (twelve series) or the fifteen individual series. These results suggest that either these series may be older than the local reference chronology utilised, 1728-1999 (Edouard, unpublished), or that Scots pine trees used for wine presses may have grown in very particular site conditions, triggering ring-width patterns different from those of the reference chronology . In addition to that, attempts

were carried out using other tree species (larch, Arolla pine) as references: no valuable crosscorrelation was obtained.

## Conclusions

A preliminary dendrochronological study of ten wine presses in the Southern French Alps evidence the multiple tree species utilized. These structures are not only made with larch: Scots pine and fir were also used.

Apparently there is no species distinction for the wine presses pieces, except maybe for joists which are mainly made in larch and lever, mainly in Scots pine. Scots pines pieces are larger and older than larch pieces. The dating of the Scots pines series will shed light both on this original heritage and on the local past pine forests.

It is now demonstrated that vine was cultivated and wine presses built, at least from the 17th c. until the end of the 19th century. It tends to fall into the demographic optimum and the Little Ice Age period, a supposed unfavorable period for viticulture in mountain areas. Then, Phylloxera epidemic, competition with Provencal wine and decline of agricultural activity, all contributed to the demise of viticulture. Later, the felling phases should be refined, maybe with the twenty others timbers not yet sampled).

Last, archaeological studies are now required to provide a context on these structures and look for any relationship with earlier periods.

## Acknowledgements

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# Age estimation of Norway spruce saplings: analysis of the cambial age at various stem heights

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## Introduction

Norway spruce (*Picea abies* (L.) Karst.) is one of the most important tree species in the forests of the mountains on the Central and South-East Europe. These forests not only play an important ecological role, but are also important for their timber production and protective functions (Brang et al. 2006, Bebi et al. 2009).

Good knowledge on tree age is crucial for the correct interpretation of age distributions and therefore for understanding forest dynamics. Usually tree age is found by counting tree rings on increment cores extracted from a position close to the base of the trees (DesRochers & Gagnon 1997) or on stem discs. Yet, in reality increment cores are usually extracted at a predetermined height, such as breast height (1.3 m) or 0.2-0.4 m above ground level (Lorimer 1980, Veblen et al. 1991). This causes several potential problems in using increment cores for age estimation. Some of these common problems are related to the challenge of exactly hitting the pith of the tree stem and to the unknown number of years between tree germination and reaching the sampling height. In addition, the innermost tree rings are often extremely narrow and hard to distinguish, which creates the possibility for larger mistakes in age estimation if only tree ring cores are used. On the other hand locally false or absent tree ringsmay cause over- or under-estimation of the true tree age (Duncan 1989, Norton & Ogden 1990). The magnitude of possible age estimation errors for each of the abovementioned limitations varies from few years to decades. Various methods have been used to minimize the errors. Missing or false rings are usually discovered in the procedure of crossdating (Yamaguchi 1991, Grissino-Mayer & Holmes 1993), while the number of missing ringson cores that fail to hit the pith might be graphically modelled (Norton et al. 1987, Duncan 1989, Villalba & Veblen 1997). Two main groups ofmethods are used to correct the age of trees estimated from cores extracted at different heights above ground level. The first method involves cutting saplings at the root collar and determining a height correction from the average basal age of saplings tothe coring height (i.e. "sapling method") (Veblen et al. 1991). A second common method is to add the average age difference between pairs of cores from mature trees taken at ground level and at coring height to every sample (i.e. "ground method") (Henry & Swan 1974, Wong & Lertzman 2001). However both methods provide accurate height correction only when trees have similar rates of early growth over time and space (Palik & Pregitzer 1995). Yet, this is often not true for shade-tolerant species, which may have extremely different growth rates under the canopy and in open conditions. In addition, differences in growth conditions between mountains locations in various locations of the world might additionally hinder using data from other sites and studies even for the same tree species.

We therefore aimed at estimating the number of years it took Norway spruce saplings from Southern European Mountain locations to grow to typical heights for coring (0.3 m; 0.5 m; 1.0 m and 1.3 m) also accounting for the effect of open and under-canopy growth conditions.

## Study sites

We conducted the study in two unmanaged subalpine *Picea abies*-dominated forests in Bulgaria, South-Eastern Europe (Fig. 1) which have similar climate and growth conditions to other spruce-dominated forests in Central and Southern Europe (Panayotov et al. 2015) . The first site is the

Parangalitsa forest reserve located in the Bistritsa valley in Rila National Park, South-Western Bulgaria. The reserve is one of the first strictly protected areas on the Balkan Peninsula and is part of UNESCO's "Man and biosphere" network. This ecosystem was formally declared a natural reserve in 1933, but before that it was already considered a protected forest in which human activities were limited only to hunting and pasturing on the alpine grasslands above the forest (Panayotov et al. 2011b). Forests are predominantly Norway spruce-dominated with age above 150 years and occupy a 250 ha belt between 1450 and 1950 m a.s.l. At lower altitudes (below c. 1650 m a.s.l.) Norway spruce is mixed with up to 70% Silver fir (*Abies alba* Mill) and up to 40% European beech (*Fagus sylvatica* L.), while close to treeline, Norway spruce is mixed with up to 20% of the Balkan endemic species Macedonian pine (*Pinus peuce* Griseb.). Additionally, Scots pine (*Pinus sylvestris* L.) co-dominates in some of the forest patches. During the last 200 years the forest was disturbed mostly by windthrows of various sizes, which affected more than 25% of the total area (Panayotov et al. 2011b, Panayotov et al. 2015). The average annual temperature at 1450 m a.s.l. is 5.2 °C and at 1950 m a.s.l. is 2.5 °C. The average annual precipitation amounts to 933 mm with a maximum in late spring and early summer (Panayotov et al. 2015).
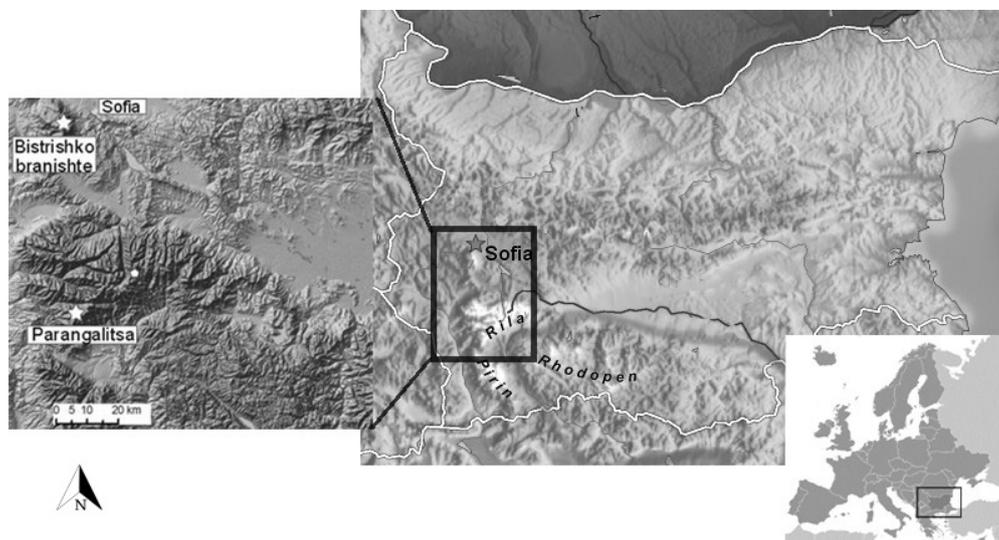


*Figure 1: Study sites.*

The second selected study site is the Bistrishko branishte forest reserve within Vitosha Nature Park, Western Bulgaria. The reserve was declared in 1934 to protect the last remnants of Norway spruce forests in thismountain region. Norway spruce-dominated forests cover 650 ha at altitudes between 1400 and 1950 m a.s.l. In the lower part (up to 1500 m a.s.l.) Norway spruce is mixed with European beech (*Fagus sylvatica* L.), Sycamore maple (*Acer pseudoplatanus* L.) and Balkan maple (*Acer heldreichii* Orph. ex Boiss.). The forest was predominantly 120-140 years old and in 2001 the oldest parts in the reserve were affected by a 60 ha windthrow, which was followed after 2003 by massive bark beetle outbreak killing the majority of the old Norway spruce trees on a territory of over 200 ha (Panayotov & Georgiev 2012, Panayotov et al. 2015). The disturbed area was left to natural development without any human interventions.

The average annual temperature is 2.3 °C at 1950 m a.s.l. while the precipitation amounts to 1228 mm, with maximum in May-June and minimum in August-September (Tsvetanov & Panayotov 2013). The bed rocks are andesite and syenite. Soils are predominantly dark mountain soils (Mollic Cambisols) and brown mountain soils (Dystric and Umbric Cambisols) with sufficient depth. In some areas of the reserve the soils lie on large spherical syenite blocks and therefore the rooting depth is limited.

## Material and methods

The sample sites were identified and mapped on the basis of forest maps and orthorectified digital aerial photographs in GIS using ArcGIS 10 software (ESRI Inc) (Panayotov et al. 2011b, Panayotov & Georgiev 2012). We designed transects in which we set 100 m$^2$ sample plots at every 50 m. In each of the sample plots we described growth conditions and randomly selected several normally developed trees for cutting. In total seventy-two Norway spruce saplings with DBH ≤ 4 cm were cut at the root collar of the stems. The root collar was identified by the shift from the presence of a pith to a central vascular cylinder (Telewski & Lynch 1991). From them we prepared 360 cross-sections from heights of 0.0 m, 0.3 m, 0.5 m, 1.0 m and 1.3 m. Thirty-three of all saplings, from which we prepared 165 stem cross-sections, were growing in open-growth conditions, which occurred after large-scale disturbances. The other 39 saplings (195 stem cross-sections) were from under the canopy of mature forest.

The cross-sections were sanded with progressively finer sand papers to ensure that the cells of tree rings were clearly identifiableand then were scanned at 1200 dpi resolution with Epson Expression 11000XL scanner. Tree rings were measured from the scanned images with the CooRecorder 7.6 software (Cybis Elektronik & Data AB). To ensure the lack of missing rings and appoint the exact calendar year in which each tree ring was produced we performed the crossdating procedure following standard methodology (Stokes & Smiley 1996). We did the crossdating with CDendro 7.6 software (Cybis Elektronik & Data AB) using regional reference chronologies for *Picea abies*from our study sites (Panayotov et al. 2011a). Normality of data distribution was checked with Shapiro-Wilk test, while significance of differences between groups with Two-Sample t-Test and the difference between the growths rates between the two reserves with Two-Sample Test for Variance. All statistical calculations were made in OriginPro 9.0 software (OriginLab Corp.).

## Results and Discussion

We chose several coring heights, which are often used in reality (0.3 m; 0.5 m, 1.0 m and 1.3 m) because in sloppy terrain above 20-25 degrees it is often impossible to sample atpredetermined height.The age variations at the four possible sampling heights were relatively small at open-growth conditions (up to 10 years) but increasedforsaplings growing under the canopy. The difference in the growth rates between the two reserves at open conditions was not significant (Two-Sample Test for Variance, p = 0.30) as well as at under canopy conditions (Two-Sample Test for Variance, p = 0.44). The differences between groups (0.0-0.3 m; 0.0-0.5 m etc. at open-growth conditions and under canopy) were significant, except for the groups 0.0-1.0 and 0.0-1.3 m at under canopy conditions (p = 0.14).

From the total material measured at open growth conditions the *Picea abies* saplings needed 7 (±4) years to grow to 0.3 m, 11 (± 4) yearsto grow to 0.5 m, 16 (± 5) to grow to 1.0 m and 18 (±5)years to grow to breast height (1.3 m). The standard deviation was up to 6 years, which means that for the majority of the saplings the actual age could be determined with an error of less than one decade (Fig. 2; Table 1).

The *Picea* saplings which grew under the canopy reached 0.3 m in  9 (±4) years, 0.5 m in 15 (± 6) years, 1.0 m in 20 (± 5) years and 1.3 m in 27 (±12) years (Fig. 2; Table 2). For the saplings which occurred under the canopy the age variations were largestat breast height – up to 48 years, and therefore age corrections to such cores is not recommended. Yet, at 0.3 m to 1.0 m height the age variations were relatively small – up to 10 years, which in terms of forest dynamics is below one age class and therefore age corrections could be applied to such cores.
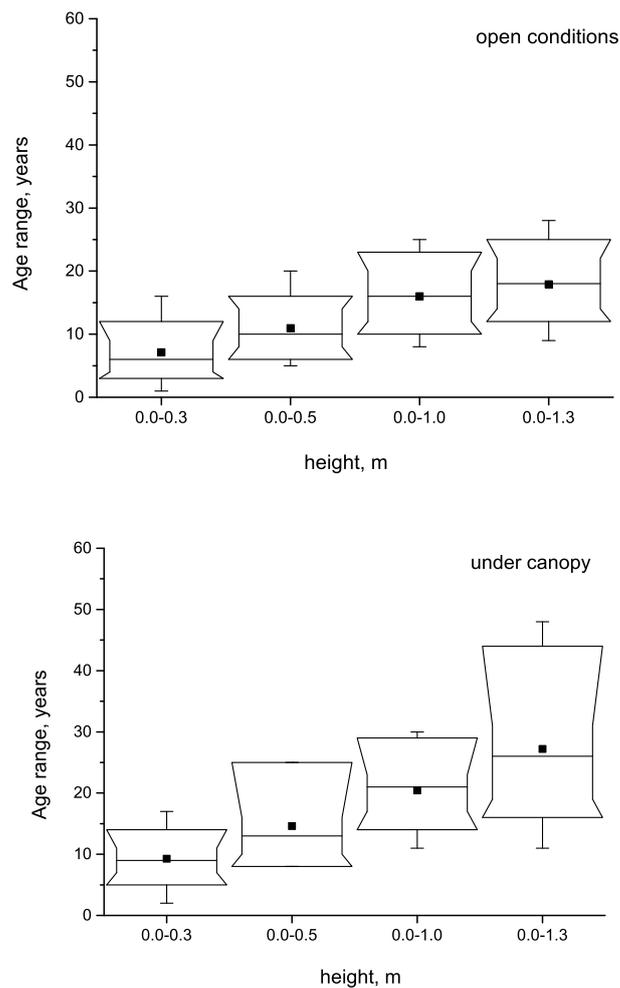
*Figure 2: Box-plots diagrams of tree age by height in open conditions / closed conditions (under canopy). The range of box-plot represents the 10th; 25th; 75th and 90th percentiles. The whisker ends represent the 1,5th and 98,5th percentiles; the median is expressed by horizontal line in the box and the mean by the square with solid fill.*

*Table 1: Main statistics for the ageof tree height classes in open-growth conditions*

| | Years to reach different height | | | |
|---|---|---|---|---|
| | 0.0 - 0.3 m | 0.0 - 0.5 m | 0.0 - 1.0 m | 0.0 - 1.3 m |
| Mean | 7 | 11 | 16 | 18 |
| SE | 0.63 | 0.70 | 0.89 | 0.93 |
| SD | 3.57 | 4.01 | 4.95 | 5.27 |
| Minimum | 1 | 5 | 8 | 9 |
| Maximum | 17 | 20 | 25 | 28 |

*Abbreviations: SE – Standard error; SD – Standard Deviation*

*Table 2: Main statistics for the age of tree height classes under canopy*

| | Years to reach different height | | | |
|---|---|---|---|---|
| | 0.0 - 0.3 m | 0.0 - 0.5 m | 0.0 - 1.0 m | 0.0 - 1.3 m |
| Mean | 9 | 15 | 20 | 27 |
| SE | 0.60 | 0.95 | 1.01 | 2.22 |
| SD | 3.71 | 5.91 | 5.07 | 12.39 |
| Minimum | 2 | 8 | 11 | 11 |
| Maximum | 18 | 32 | 30 | 71 |

*Abbreviations: SE – Standard error; SD – Standard Deviation*

Errors in height corrections limit inferences that can be made from age-class distributions because of over- or under-estimation of real tree age.Coring the trees at the base of the trunk or up to 0.3 m height may provide a fairly reliable estimate of the actual tree age. When sampling near the base of the tree is not possible,age correction may be applied, but the possible error gets too high for coring heights above 1 m for samplings which grew under the canopy.

## Conclusion

Our data indicated that Norway spruce saplings needed almost the same number of years to reach 0.5 m in open conditions and under the canopy (11± 4 and 15 ± 6 years respectively). At bigger heights the differences between both groups increased, which means that if age corrections are applied they should be specific for trees in open conditions and trees under the canopy. At the same time the relatively small deviations from the mean (less than 10 years) for ages at heights of up to 1 m allows age corrections for cores extracted up to this height. Our data gives the opportunity to suggest for age corrections for Norway spruce saplings at open growth conditions of 7 years for height of 0.3 m, 11 years for height of 0.5 m, 16 years for height of 1.0 m and 16 years for height of 1.3 m.

For saplings grown under the canopy suggested values for height correctionsare 9 years for 0.3 m, 15 years for 0.5 m and 20 years for 1.0 m. Age correction for cores extracted at heights above 1.0 m is not suggested, or if needed, it could be 27 years with high chance of error.

## Acknowledgements

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# Growth responses of *Pinus halepensis* Mill. plantations to climatic variables in Aurès mountains, Algeria

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## Introduction

Global climate change is expected to cause a progressively increased frequency and severity of drought events in the Mediterranean Basin (IPCC 2014). This challenge is particularly severe in arid and semi-arid regions like North Africa where the resource limitations come not merely from a shortage of water but from the high variability of precipitation in space and time (Touchan et al. 2011). The Mediterranean Basin is one of the world regions with the largest proportion of planted forests (FAO 2006). Pines were the tree species most commonly planted due to their fast growth rates in open, xeric conditions, promoting rapid canopy closure and eventual facilitation of the establishment of late successional hardwoods (Zavala & Zea 2004). Recent drought-induced in several Mediterranean pine species have been reported (Sánchez-Salguero et al. 2010; Sarris et al. 2011) considering planted pine forests more vulnerable areas to these environmental alterations (Sánchez-Salguero et al. 2012, 2013). In Algeria the area occupied by forests is ca. 4.7 million hectares and more than 15% are plantations (Ghazi 2009). Despite the low growth rate of afforestation in semi-arid areas, the artificial ecosystems are a valuable national heritage by the multiple functions of economic development to the ecological, economic or even social services for Algerian population. Nevertheless, the effects of climate changes and droughts events on tree growth have been rarely evaluated in pine afforestations despite its ecological and economic importance in North Africa. *Pinus halepensis* Mill, which is one of the best adapted Mediterranean tree species to drought (Pausas 2004), represents a major forest capital in Algeria. However, the forecasted climatic conditions for Algeria could reduce tree productivity in these pine plantations causing drought-induced dieback processes in drought-prone forests throughout North Africa (Kherchouche et al. 2012; Linares et al. 2013). Climatic trends in northern Algeria, during the second half of the 20th century were characterized by a high drop of spring precipitation (Slimani et al. 2014). Such increase in spring aridity was particularly noticeable in mountains from Aurès (Touchan et al. 2011; Slimani et al. 2014). Several studies summarized in De Luis et al. (2014) carried out investigations using dendrochonology methods on Aleppo pine natural Mediterranean forests. However, there is a lack of knowledge on *Pinus halepensis* plantations especially regarding growth responses to climate variations and the effects of droughts in North Africa regions. In this study, we used dendrochronological methods to evaluate the relationships between radial growth and climate in *P. halepensis* plantations located in northeaster Algeria, Aurès mountain area. This study aims to (i) analyse the radial growth trends and (ii) to investigate the relationships among growth patterns and sensitivity to climate and recent droughts.

## Materials and methods

### Site description

The study area is located 47 Km southwest of Batna (capital of Aurès) in Algeria at an altitude of 1100 m a.s.l (35°26' North, 5°50' East) (Fig. 1). Climate is Mediterranean semi-arid with cold wet

winters and hot dry summers. The average annual precipitation is 337 mm with high annual and seasonal variability (inter- and intra- annual). The average annual temperature is 15.4°C, ranged between 8.2°C in the coldest month (January) and 22.9°C in the warmest month (July) (1980-2012 period). Annual drought period (P < 2T) which characterize the study area is extended from the middle of May to the middle of October (Fig. 2). The xerothermic character of this site is reinforced by substrate nature. The bedrock is calcareous and dolomite, and covered by a superficial soil of a well-balanced textural class of loam–clay–sandy.
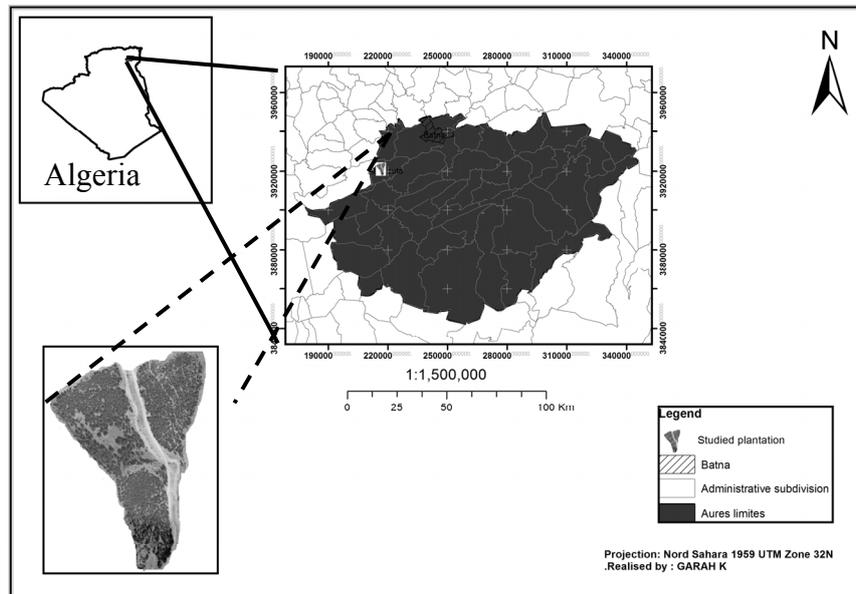


*Figure 1: Study area location in Aurès Mountains (Algeria).*

The study area included 400 ha of Aleppo pine afforestation planted in 1973, with an initial stand density of 1600 stems per hectare. The aspect ranged between NE and SE facing slopes which values from 10 to 20%. The plantation was mainly intended to fight against erosion and the studied forest has not been managed since its establishment. The co-dominant canopy is sparse and composed by *Quescus ilex* Mill., *Juniperus oxycedrus* Sibth. & Sm, *Juniperus phoenicea* L., *Cupressus sempervirens* L., *Artemisia campestris* L., *Globularia vulgaris* L. and *Rosmarinus officinalis* L.

### Climate data

We used climate data from AïnSkhouna metereological station (Batna) (35°45'19''N, 06°19'E), the only nearest station providing the most reliable and complete data. We used raw data (regional series of monthly precipitation and temperature) over a period of 32 years (1980-2012). We also calculated an annual water deficit or drought index (P-PET, in mm) since this may be a better indicator of the effects of water availability on tree growth than temperature or precipitation itself (Sánchez-Salguero et al. 2010). This drought index is defined as the difference between the accumulated precipitation (P) and the potential evapotranspiration (PET) (Thornthwaite 1948). Thus, lower (higher) index values indicate higher (lower) water deficit. In addition, a long-term series of drought severity based on the annual self-calibrating Palmer Drought Severity Index (scPDSI) was derived from CRU TS 3.2 dataset (Mitchell & Jones 2005). The scPDSI shows more negative values in years with more severe drought (Sánchez-Salguero et al. 2012).
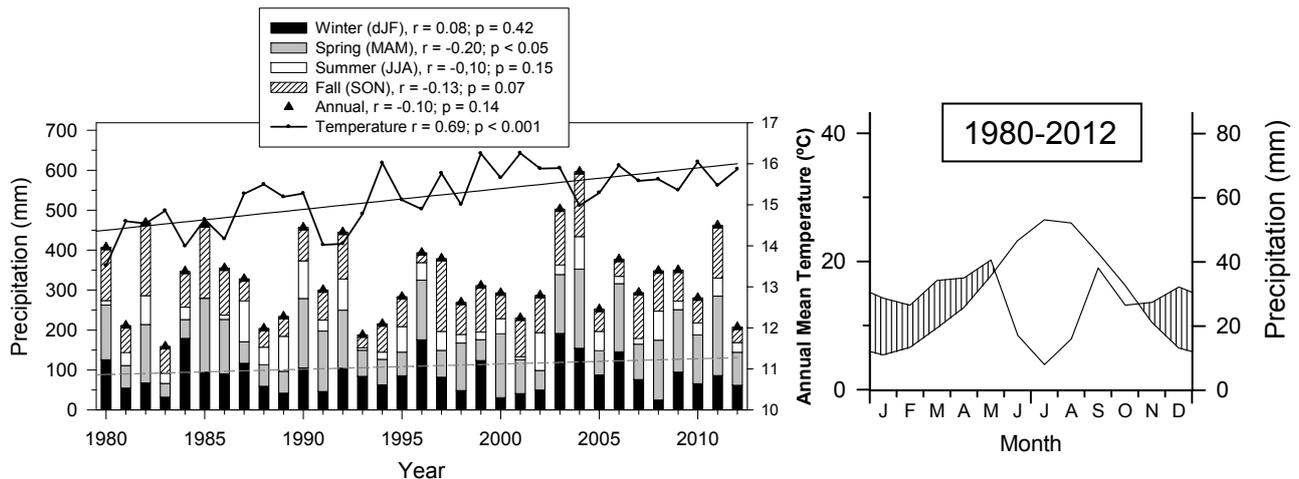
*Figure 2 : Trends in annual mean temperature and seasonal precipitation in the study area for the period 1980-2012 (left); and climate diagram of the study area (right).*

## Sampling design and dendrochronological methods

Fieldwork took place during winter 2012-2013 throughout the studied Aleppo pine stands. We collected sampling from 12 circular plots of 0.40 ha each, spaced 50 meters and installed along a NE-SE transect. In each plot, at least 4 trees were measured (DBH, 1.3 m above the highest root) and sampling by classical dendrochronological procedures, i.e., two cores per tree, at 1.3 m with a Pressler increment borer along the direction perpendicular to the maximum slope to avoid reaction wood. A total of 90 cores were collected from the 45 selected trees. The material was air dried and sanded with sandpapers of successively fine grain until its growth rings were clearly visible and then the cores were visually cross dated (Yamaguchi 1991). The polished surfaces of the cores were subsequently scanned to a resolution of 300 dpi and annual growth rings were measured to the nearest 0.01 mm using the "*ImageJ*" software (https://imagej.nih.gov/ij/). Cross-dating quality of the tree-ring series was checked using the COFECHA program (Holmes 1983).

In order to evaluate the radial growth trends, different chronologies were established and evaluated (quality) using standard dendrochronological statistics: Mean sensitivity (MS), a measure of the relative difference of growth between consecutive rings, intercorrelation coefficient (Rbt), the mean annual ring-width increment (CM), and the first-order autocorrelation (AR1), a measure of similarity in width between consecutive rings (Fritts 2001). To analyze changes in growth patterns we calculated the annual basal area increment (BAI) obtained by the following formula: $BAI = \pi (R^2_t - R^2_{t-1})$, where R is the radius of the tree and t is the year of tree-ring formation (Biondi & Qaedan 2008). We also obtained the residual chronology of ring width indices by eliminating the long-term growth trends related to increasing tree size and age and reducing the first-order autocorrelation. Detrending of the tree-ring series was done by fitting a negative exponential curve to each series. Dimensionless residual indices of tree growth were produced by dividing the raw ring width values by the values of the fitted curve and performing autoregressive modelling of the results with the program ARSTAN (Cook 1985).

## Growth responses to climate

The relationships between radial growth and climate were evaluated using the residual chronologies and the local climate series of mean monthly temperature and precipitation. Growth-climate relationships were quantified using Pearson correlation coefficients. Growth indices and monthly climatic series were compared from August of the previous year to October of the year of tree-ring growth because this is the most influential period for radial growth of the studied pine (De Luis et al. 2007; Camarero et al. 2010). Correlation analyses were performed using the program

DENDROCLIM 2002 (Biondi & Waikul 2004). We also analyzed BAI trends and their relation with climate variables (annual and seasonal drought index and precipitation) comparing BAI and climate temporal series, with emphasis on the effects of pointer (driest) years. We estimated the pointer years using the macro «*POINTER*» developed by Merian (2012) under the "R" programming language by choosing a 10% threshold of the average relative deviation, and 75% of trees.

## Results and Discussion

### Dendrochronological characteristics

The mean density of the studied stand was 1023 trees/ha which has been maintained by the lack of management, producing extremely slender trees for 40 years old forests (Table 1). However, it is recommend 400 trees/ha for this age in Aleppo pine plantations (Orazio 1986). Although, it has not been considered in this study, the high stand density reflects a high level of competition for light, water and resources among trees (Linares et al. 2010). These relations have noticeable effects on the radial growth of the studied pine specie (Sánchez-Salguero et al. 2010, 2015).

*Table 1: Description of the radial growth series.*

| | |
|---|---|
| Total sampled trees | 45 |
| Number of retained trees | 30 |
| Number of retained cores | 60 |
| Total tree rings in all series | 1781 |
| Average height of sampled trees | 7.5 m |
| Average diameter | 13.66 cm |
| Stand density (trees/ha) | Min: 640 Max: 1420 Mean: 1023 |

Mean tree-ring width in the period 1982-2012 was 1.77 mm. We noted that the studied Aleppo pine would require 9 years to achieve a breast height level at 1.30 m. The radial growth has a higher annual variability ranges between 0.27 mm/year and 4.41 mm/year (Table 2). Our results shows higher differences in mean sensitivity and first-order autocorrelation than other wettest Aleppo pine forests (De Luis et al. 2014) suggesting higher vulnerability of Aleppo pine plantation to climate changes in consonance with findings of previous studies (e.g., Sánchez-Salguero et al. 2010).

*Table 2: Dendrochronological statistics of sampled trees.*

| | |
|---|---|
| Mean annual increment (CM) | 1.77 mm |
| Max. annual ring-width | 4.41 mm |
| Min. annual ring-width | 0.27 mm |
| MS | 0.590 |
| Rbt | 0.749 |
| AR1 | 0.554 |
| EPS | 0.93 |

Mean temperatures in the study area have significantly increased since 1980, whereas spring rainfall has decreased in the same period (Fig. 2). The driest years were observed with very narrow rings (1993, 2001, 2005, 2008, 2012) and wettest years with wide rings (2002, 2003, 2004, 2009) (Fig. 3). Among these pointer years of growth, the 2001 is the most pronounced pointer year (Slimani et al. 2014) by the decrease in spring precipitation (Fig. 3). BAI trends showed sharp

reductions during these dry years (Fig. 3). We also noted a greater increase in growth rate during wet years.
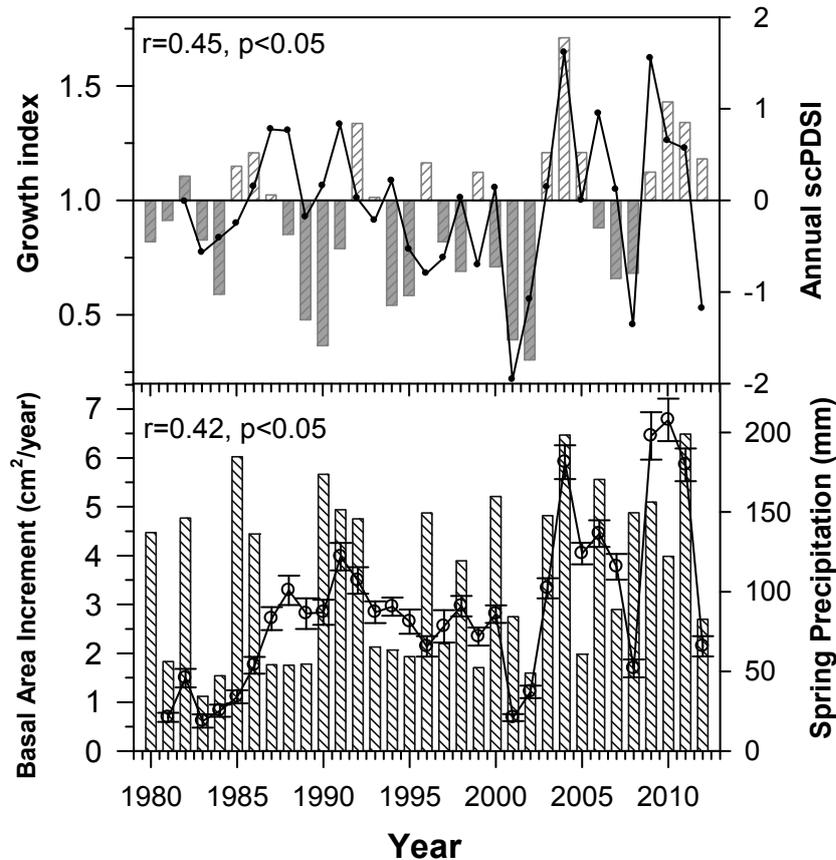


*Figure 3: Residual tree-ring width mean chronologies of planted P. halepensis stands (black line) as related to Annual scPDSI index (grey bars) –upper graph–, and Basal area increment (black line with dots) in relation to spring precipitation (hatched black bars) –lower graph–. The correlation between growth series and climate variables is shown inserted on the figure.*

*Growth response to climate*

We found significant positive (negative) relationships between growth and precipitations from April to June (temperatures) (Fig. 4). At long-term period, the growth was positively related to the spring rainfall (Fig. 3). Considering climate-growth relationships with seasonal precipitation, we found significant relationships between growth and winter and spring precipitations (Nicault et al. 2001; Papadopoulos et al. 2001; Slimani et al. 2014) (Fig. 4), whereas precipitation in summer showed lower correlation with growth (but see Sánchez-Salguero et al. 2010).
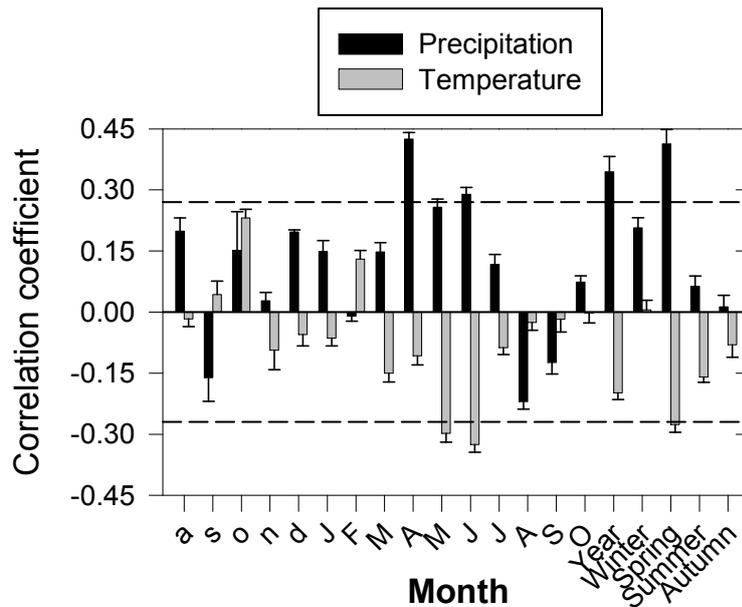
*Figure 4: Relationships between individual radial growth (tree ring-width indices) and monthly or seasonal climatic variables (T, mean temperature –grey bars; P, total precipitation –black bars). Growth is related with climate data from the previous (months abbreviated by lowercase letters) and current (months abbreviated by uppercase letters) years, being the current year that of the tree-ring formation. The significance levels (P < 0.05) are indicated by dashed horizontal lines. Errors bars show the standard error.*

Fig. 5 shows drought period extended over 7 months, starting from April until October. Radial growth of Aleppo pine plantations in Algeria is mainly conditioned by the intensity of spring-early summer drought and eventually related to September-October precipitation (Serre-bachet 1992; Slimani et al. 2014) (Fig. 5). The decrease in water availability in late spring and early summer seems to be a major driver of tree growth causing BAI decline during extreme drought years (Nicault et al. 2001; Camarero et al. 2010) (Fig. 5).
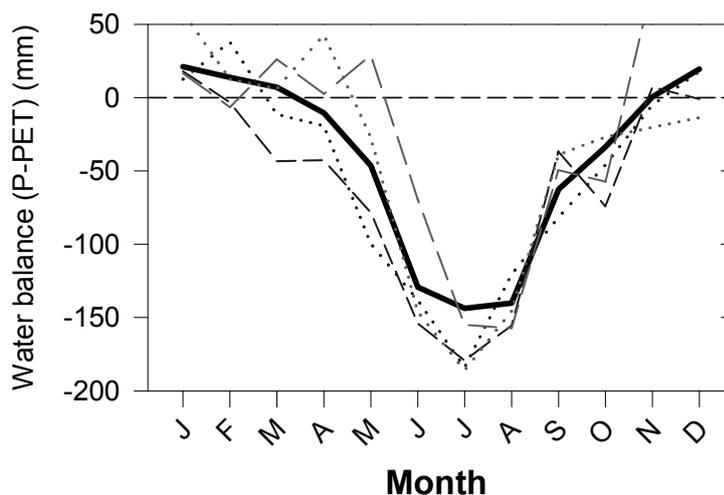


*Figure 5: Average drought index (black line), dry years (dark dashed line for 2001, and dark dots for 2005) and wet years (grey dashed line for 2004, and grey dots for 2009).*

The increased climate variability associated with the current climate change could lead to growth decline in Algerian pine plantations under lack of adaptive management (Kherchouche et al. 2012; Sánchez-Salguero et al. 2012). Our study provides further evidence about potential vulnerability of Aleppo pine plantation in Algeria to climate change by comparing climate-growth responses of

densely planted forests with natural stands (Touchan et al. 2011; De Luis et al. 2014). Rainfall variability was responsible of the sharp growth declines in 1993, 2001, 2005, 2008 and 2012, but also caused high basal area increment in wet years (e.g., 2002, 2003, 2004 and 2009) (Fig. 5) (Sánchez-Salguero et al. 2012, 2013). Furthermore, more research is required to unravel the relative contributions of long- (e.g., temperature rise and competition) and short-term (e.g., extreme droughts) climatic stressors on Aleppo pine growth in Algeria. Specifically, the forecasted warming-induced water deficit in spring could trigger future drought-induced growth declines in these planted forests. The lack of silvicultural management of the studied plantations led to the existence of dense *P. halepensis* stands at sites that may be hereafter too xeric for the performance of this species (Del Campo et al. 2014). Even in cases of severe spring-summer drought, however, drought stress could not the sole factor causing growth reductions but rather a long-term factor that weakens the vigor of the trees and, in combination with unfavorable site conditions, renders them susceptible to additional stressors such as insect defoliation (e.g., Sánchez-Salguero et al. 2013). Thinning of drought prone planted forests should reduce competition between trees for soil water and enhance the species' adaptive capacity (increasing resilience and decreasing vulnerability) to withstand drought stress in Algeria.

## Conclusion

In northern Algeria, annual temperature has increased and spring precipitation has declined during the growing period since 1980 leading to a long-term reduction in water availability. These regional climatic changes affected planted *P. halepensis* stands and these trees experience stronger growth reductions during severe drought episodes than those from natural ones with similar site conditions (Pasho et al. 2011; Girard et al. 2012). The high tree to tree competition as a result of lack of silvicultural practices in conjunction with increases drought event can be drivers of potential future forest decline in Algerian plantations under the forecasted warmer and drier conditions for the Circum-Mediterranean area. Moreover, new research is required in Algerian Aleppo plantations to assess the mitigation effects of thinning treatments, which could enhance BAI in favorable years and improve the recovering of tree growth after droughts or other disturbances (Alfaro-Sánchez et al. 2014).

## Acknowledgements

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# SECTION 4

# WOOD ANATOMY

# Ring width and vessel lumen area of *Fagus sylvatica* in years with spring and summer drought

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## Introduction

Changing climate conditions are likely to influence and modify future forest growth in central Europe as extreme drought events are expected to increase in frequency and intensity (Bréda et al. 2006). *F. sylvatica* (European beech) is considered vulnerable to drought (e.g. Zimmermann et al. 2015) and often shows a strong reduction in radial growth as an effect of extremely dry years (e.g. Zang et al. 2011; Meinardus et al. 2012). As temperatures rise and the precipitation regime is likely to shift to drier conditions during the vegetation period in southern Germany, future growth conditions are assumed to become less favourable for *F. sylvatica* (Rennenberg et al. 2004; Friedrichs et al. 2009). Jump et al. (2006) report a growth decline of *F. sylvatica* in Spain induced by warmer temperatures and a constant amount of precipitation. Zimmermann et al. (2015) studied the effects of climate warming on *F. sylvatica* and co-existing broadleaved tree species at three study sites in Germany. They found that only *F. sylvatica* showed an increasing number of negative pointer years at all stands and a decreasing radial growth in the driest study site since 1980, when summer temperatures and the intensity of droughts increased. They assume that *F. sylvatica* may lose its competitive advantage at drier sites due to proceeding climate change. According to Rasztovits et al. (2014) the distribution of beech may in the future be stronger limited by increasing frequency and severity of climatic extreme events than by long-term climate means.
Although most studies agree about the drought sensitivity of *F. sylvatica*, they often disregard for when a drought occurs. It can be assumed that the timing of a drought has a different impact on tree growth and on the vascular system of drought-affected trees (Fonti et al. 2010).
In this study we analysed the effects on ring-width and vessel lumen area of *F. sylvatica* in years characterized by drought episodes in spring and summer.

## Material and methods

### Study sites

Both study sites are located in Northern Bavaria (Fig. 1) and represent mixed deciduous forests consisting mainly of *Fagus sylvatica* and *Quercus petraea*. For comparison, we chose two study sites which differ in their climatic conditions. The study site Waldbrunn is situated in the warmest and driest region of Bavaria. Mean annual temperature is 9.4°C and the annual precipitation sum amounts 575 mm. To compare the effects of the drought events on the trees at a drier location to a location with wetter climate conditions, we chose study site Ebrach, which is cooler and more humid, with mean annual temperatures of 7.9°C and a mean annual precipitation sum of 787 mm (all mean values calculated for the period 1971-2000, DWD 2010).
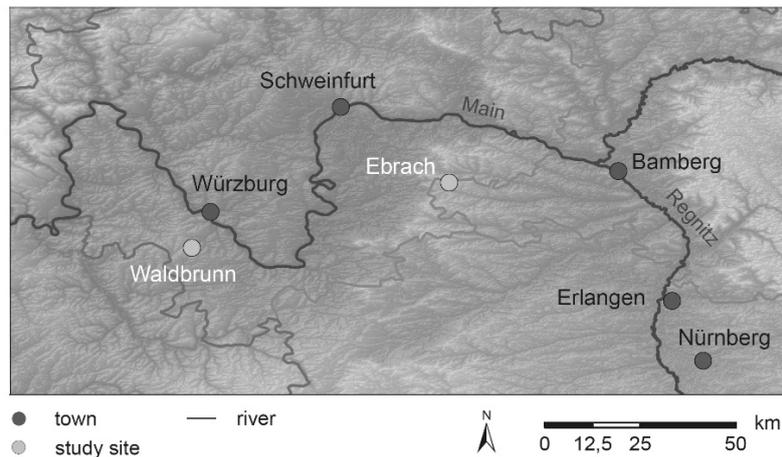
*Figure 1: Study sites Waldbrunn and Ebrach (Northern Bavaria, Germany).*

## Preparations and measurements

Ring width of two increment cores of 15 dominant beech trees was measured for each study site by using a LINTAB linear table (Rinn, Heidelberg, Germany). The software TSAP-Win (Rinn,Heidelberg, Germany) was used to cross-date the ring-width series visually and statistically.
To measure vessel lumen area (Fig. 2) we prepared thin sections of five beech cores from each site, respectively, stained them with safranin, red and astra blue and took digital pictures with a microscope camera before we manipulated the images to enhance the contrast (Fonti et al. 2009). Wood anatomical analysis was performed using the software WinCELL (Regent Instruments, Canada).
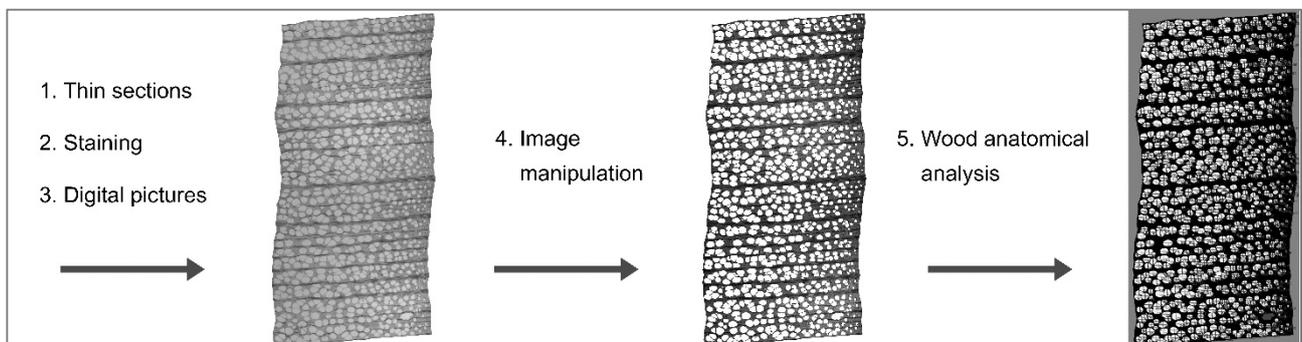


*Figure 2: Preparing steps for wood anatomical analysis*

## Drought determination using SPEI

To determine seasonal drought events we used the Standardized Precipitation Evapotranspiration Index (SPEI), which represents a multiscalar, site specific drought indicator (Vicente-Serrano et al. 2010; Vicente-Serrano et al. 2013). SPEI 3 values wereobtained for June and September, including the cumulative water balance of the previous three months, respectively. A drought episode in spring or summer time was detected, when SPEI 3 < -1 in June or September, respectively (Global SPEI database, http://sac.csic.es/spei/database.html).

## Statistical analysis

We prepared boxplots showing the ring width and the vessel lumen area of the trees for the years with drought episodes in spring and summer (1964 and 2003), including the year prior to the drought episode and the following two years.

## Results

### Ring width

During years with both spring and summer drought (1964 and 2003), ring width declines considerably at both study sites (Fig. 3a, 3b). After the drought in 1964 trees start recovering in the following year 1965 and regain their normal growth level (as defined by the ring-width prior to the drought) again in the second yearfollowing 1966.

The reaction of ring width is different after the exceptionally warm and dry year 2003: The median value of the ring width at study site Waldbrunn is already slightly higher in the first and second year following the drought. At the wetter site Ebrach, ring width continues to decline in 2004 and begins to recover only in the second year after the drought.

### Vessel lumen area

At both study sites the vessel lumen area in 1964 shows no irregularities compared to the values of the surrounding years (Fig. 3c). In 2003, the vessel lumen area is slightly larger at both sites than in the year before. Similar to ring width, vessel lumen area at both study sites decreased only in the first following year after the drought and started recovering in the second following year (Fig. 3d).
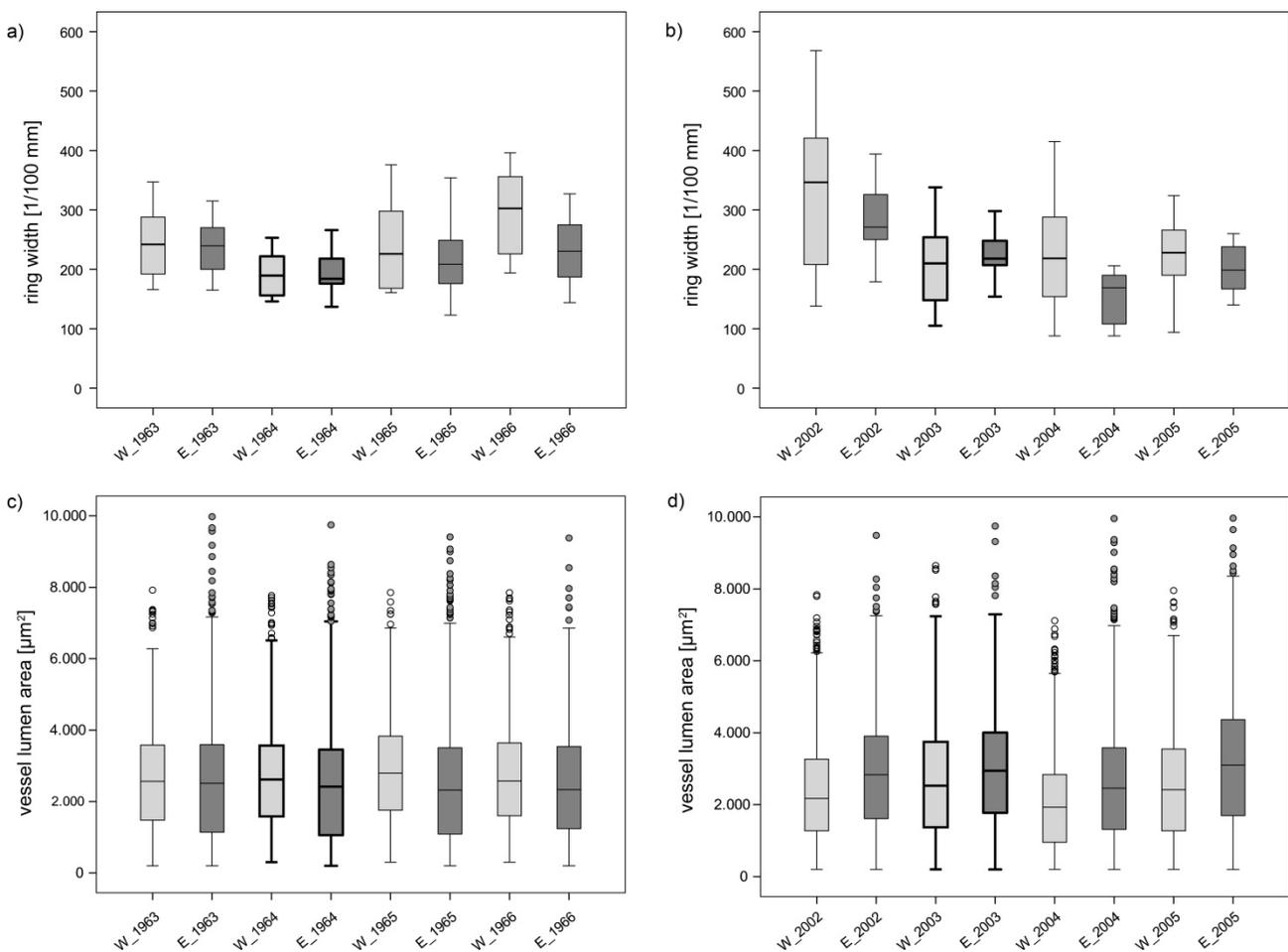


*Figure 3: a and b)    boxplots of ring width (Waldbrunn: 15 trees, Ebrach: 14 trees);c and d) boxplots of vessel lumen area (Waldbrunn: 5 trees, Ebrach: 5 trees) (light grey: study site Waldbrunn;dark grey: study site Ebrach; boldly framed: drought year)*

## Discussion and Conclusion

Using SPEI 3 of June and September we determined two years with droughts in spring and summer (1964 and 2003) and analysed the impact of these dry conditions on ring-width and vessel lumen area of *Fagus sylvatica* at two study sites.

Although both years exhibit droughts during the growing season, the impact on the wood parameters is very different. Ring-width declined in 1964 at both sites while the dry conditions seem not to have had an influence on vessel lumen area. In 2003, ring-width decreased again at both study sites in the drought year, but continued decreasing in the following year only at the wetter site, Ebrach. Vessel lumen area increased slightly in the drought year but decreased strongly in the first year following the drought. Both wood parameters began recovering only in the second year after the drought, possibly as an adaptive mechanism to adjust hydraulic conductivity (Oladi et al. 2014).

An explanation for the different recovery behaviour of the wood parameters after the drought years could be the climatic conditions of the first following year. Both study sites received above average precipitation during the growing season in 1965, while temperatures were mostly below average (data not shown). These conditions might have supported the recovery process since beech prefers cooler and moister climate conditions. In contrast,precipitation was mostly below average at both study sites during spring time and early summer in 2004 (data not shown), which might have led to a further descent of ring width and vessel lumen area values in this year.

## Acknowledgements

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# Combination of common microscopic techniques and X-ray microtomography for wood anatomical analyses

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## Introduction

For many ecological research questions and for applied forest sciences it is mandatory to analyse wood anatomical characteristics of trees. Traditionally, descriptive and quantitative analyses of wood anatomical traits for wood identification and ecological analyses are conducted using thin-sections and light microscopy (Gärtner & Schweingruber 2013). However, this common technique is time-consuming, requires a precise preparation and is prone to error due to technical obstacles (e.g. air bubbles, inconsistent thickness, water droplets).

Therefore, the timesaving technology of high resolution X-ray microtomography, like it is commonly used for medical investigations or material science, has become increasingly popular within the dendroecological community since the last decade (Brodersen 2014; Mayo et al. 2010; Steppe, et al. 2004; van den Bulcke et al. 2009). One reason is that this analysis obtains the two-dimensional "Orthoslices" as well as three-dimensional composites of a given wood sample. Thus, the transversal, the radial, and the tangential section of a sample can be analysed simultaneously within one measuring process. In this paper we show that the combination of these "standard and modern" techniques offers a great opportunity and facilitation for wood identification and anatomical analyses, particularly when working with tropical tree species. In our study we used branch wood collected from the coniferous species *Podocarpus oleifolius* D. Don (Podocarpaceae) and the evergreen broad-leaved species *Alchornea lojaensis* Secco *(*Euphorbiaceae). Both are common and ecologically or commercially important tree species of the evergreen lower montane forest in the Podocarpus National Park in South Ecuador (Homeier & Werner 2008). However, knowledge about wood anatomical parameters of these species is still sparse (Secco 2008).

## Material and Methods

### Sample collection

Branch samples were collected with pruning shears at a tree height between eight to 12 meters at an elevation between 2020 and 2150m a.s.l. within the research area "Reserva Biológica San Francisco" (RBSF). To ensure maximum accuracy for our descriptive wood anatomical analyses we combined common microscopic preparation techniques with X-ray microtomography.

### Common microscopic preparation techniques

Each specimen was dehydrated with increasing ethanol concentration series and rotihistol, embedded in paraffin and cut into thin-sections of 10µm thickness (Rossi et al. 2006) with an electronic rotation microtome (Leica, Germany,). All thin-sections, cleaned of remaining paraffin, were stained with FCA solution (a mixture of Fuchsine, Chrysoidin and Astra blue) after Etzold (2002) and embedded in Canada balsam. Digital photos with a varying magnification between 4x to 64x (Leica, microscopic system) were taken and merged together.

### 3D X-ray microtomography

High-resolution X-ray microtomography (Brodersen 2014; Mayo et al. 2010; van den Bulcke et al. 2009) was applied with the Phoenix nanotom m CT (GE Measurement & Control) at the Bavarian

State Collection of Zoology (Munich, Bavaria, Germany). Since the final resolution of the 3D model increases with decreasing sample size we determined a maximum sample size of 1mm$^3$ to obtain sufficient sample resolution. 1440 projections were prepared with a molybdenum target at 60 kV and 240 µA for *A. lojaensis* and for *P. oleifolius*, respectively, leading to a volume dataset with an isotropic voxel resolution of 1.7 µm. A rotation step size of 0.25° was used. Final 3D processing was conducted with the software Amira (version 5.5.0).

**Results**

*Advantages of X-ray microtomography*

Figure 1 illustrates 2D and 3D Data by the Amira 5.5.0 software – in that our case the example of *P. oleifolius* is shown. Transversal (Fig. 1A), radial (Fig. 1B) and tangential (Fig. 1C) orthoslices (equivalent to thin-sections) can be quickly realized without cutting or injuring the specimen. Important characteristics of the wood anatomy of the species, like distinct growth ring boundaries by radially flattened tracheids and uniseriate wood rays can easily be identified, etc. The 2D Orthoslices can be edited along the three axes and finally combined in a 3D model (Fig. 1 D).
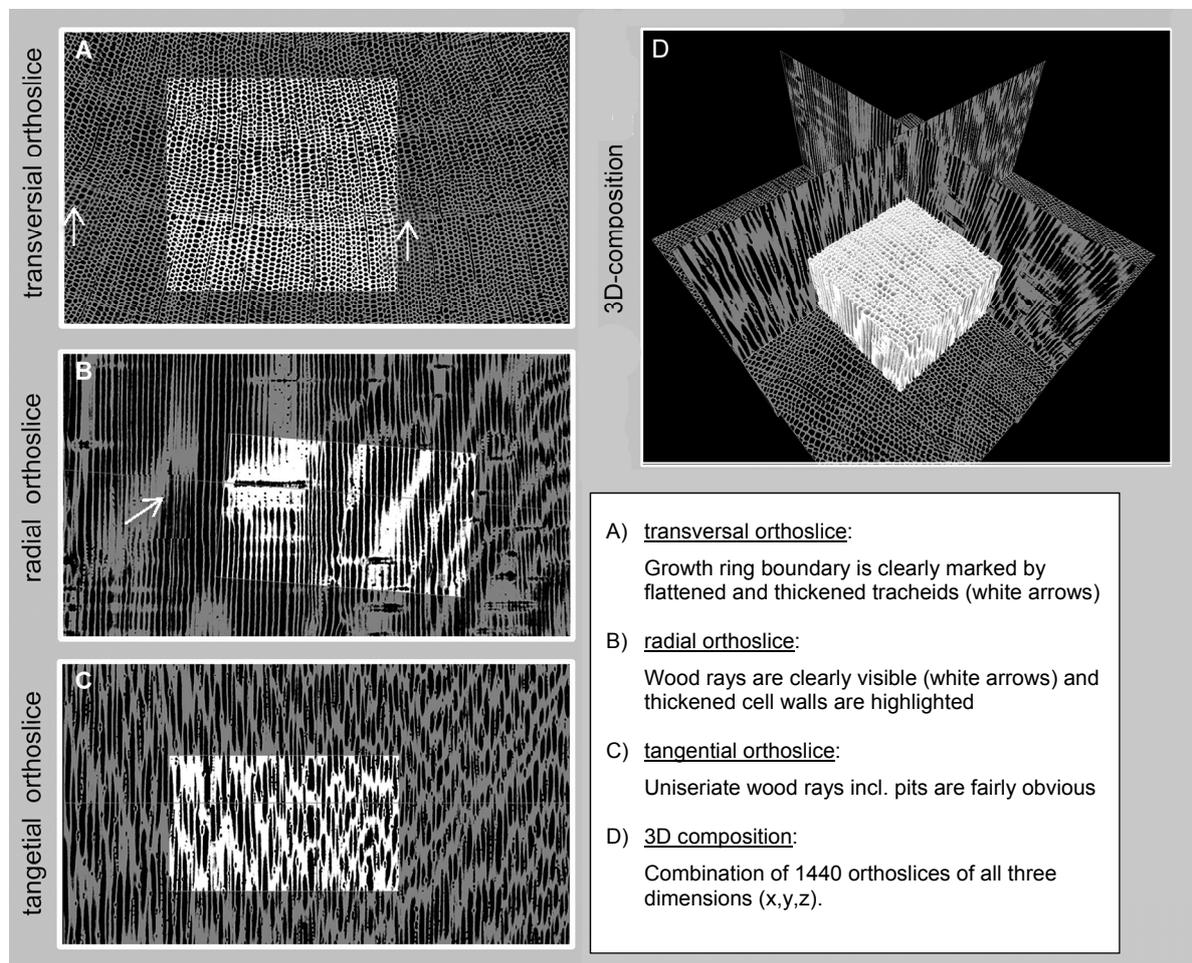


*Figure 1: Example of x-ray microtomography (study species: Podocarpus oleifolius)*

*Wood anatomy of A. lojaensis*

The combination of high-resolution X-ray microtomography (Fig. 2A) and microscopic thin-sections enabled a detailed, multifaceted insight of the wood anatomical traits of *A. lojaensis*. Our results revealed that the distinctness of growth boundaries varies considerably along the tangential direction (Spannl et al., 2015 submitted). Growth boundaries are often distinct, formed by radially

flattened and thickened libriform fibers (Fig. 2B, black box). However, distinctness of growth boundaries abruptly peters out in some parts around the branch circumference, and hence a continuous distinct growth boundary is not always present.

The vessel distribution is diffuse porous and consists of two different vessel types. The majority of the vessels include short multiple rows between 2 to 5 vessels. However, 30 % of all vessels were detected as solitary vessels embedded in scanty paratracheal parenchyma. Simple perforation plates (Fig. 2C, black box) and alternate positioned intervessel pits were detected by the 3D analyses. Non-septated libriform fibers strengthen the wood structure, which is characteristic for woody species of the Euphorbiaceae family (Carlquist 1984). Rays are exclusively uniseriate, hetero-cellular and occasionally with canals.
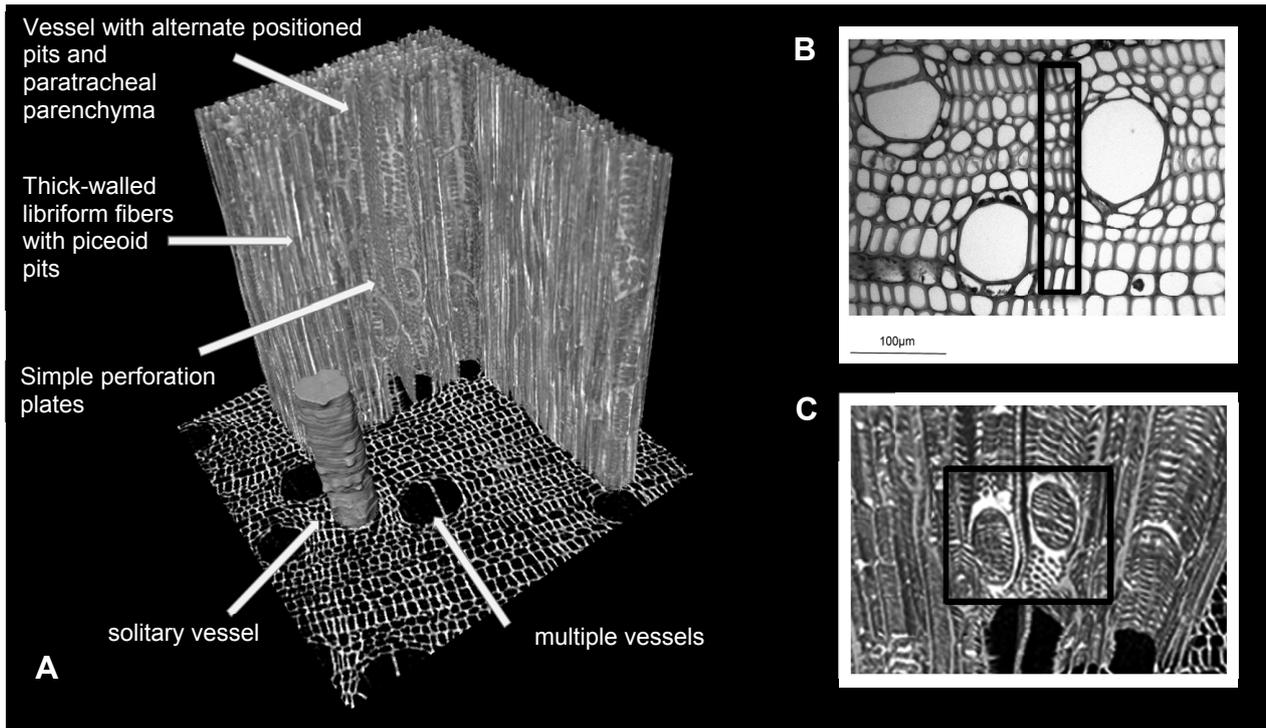


*Figure 2: Overview of x-ray microtomography and transversal thin-section (Example Alchornea lojaensis).*
  A)  *3D model of A. lojaensis. Main characteristics of the wood anatomy are marked with arrows. A single vessel is segmented.*
  B)  *Transversal thin-section of A. lojaensis. Flattened and thickened libriform fibers are highlighted by a black box.*
  C)  *Close-up view of simple perforation plates, highlighted by a black box.*

## Discussion and outlook

In this study, we highlighted the advantages of a dual methodological approach with X-ray microtomography and common thin-sections to detect the major wood anatomical structures of two tropical tree species. The two examples have illustrated that the optimal anatomical analyses can be achieved most successfully by the combination of both techniques, because each of those provides numerus benefits. One of the greatest advantages of the X-ray microtomography is that the wood sample can be set for multiple uses, as all "orthoslices" are virtually cut along three different axes. Further, the opportunities provided by this technique are much more far-reaching than those briefly illustrated here, including e.g. volume rendering, segmentation (Fig. 2A, see solitary vessel), surface visualizations, video editing, etc. (e.g. Brodersen 2014).

However, common wood anatomical techniques were still very valuable, because specific staining methods (Etzold 2002, different degrees of colour brightness) of different cell types simplified the identification of functional cell types much better than in monochromic images. In particular the case of *A. lojaensis* revealed that e.g. thickened secondary walls of libriform fibres (Fig. 2b) were clearly better visible, by using stained thin-sections. However the structure of the perforation plates

of the vessel elements (Fig. 2C) was better visualized by x-ray microtomography, enabling an insight view of the axial pathway of the vessel.

The combination of both techniques showed that the formation of annual rings varied considerably between the samples. While the conifer species *P. oleifolius* formed distinct growth zones due to radially thickened and flattened tracheids, *A. lojaensis* showed a rather interrupted, indistinct pattern of growth boundaries. Beside the fact that both tree species belong to different plant functional types, that might seem exceptionally at a first glance, however this is a special, well studied feature of tropical species growing under the same site conditions, but showing different distinctiveness and periodicity of increment zones (Worbes 1999).

According to our findings we therefore recommend a combination of both techniques for detailed descriptive and quantitative wood anatomical analyses.

## Acknowledgements

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## Gerhard Helle

Dr. Gerhard Helle is senior scientist and head of dendrochronology laboratory of Section 5.2 at the German Centre for Geosciences GFZ in Potsdam. He is specialist for stable isotope dendroclimatology. His current interest is the invention and optimization of techniques for ultra high-resolution intra-annual isotope studies in tree-rings. These techniques shall help studying the climate and isotope signal transfer from atmosphere into tree-rings. Another objective of his reasearch is the natural climate variability since the last Late Glacial as reflected in tree-ring stable isotopes. Dr. Helle is teaching Dendrochronology at the FU Berlin.

## Holger Gärtner

Dr. Holger Gärtner (1965) studied Geography and Geology at the University of Heidelberg, Germany. In 2001 he finished his PhD on variations in annual growth rings of roots caused by exposure due to various geomorphic processes. Since 2002 he is working as a research scientist specialized on wood anatomy at the Swiss Federal Research Institute WSL, Birmensdorf, Switzerland. His current research interests in focus on environmental changes and the resulting effect on the anatomical structures of various tree and shrub species. H. Gärtner has teaching assignments for Dendroecology at the University of Zürich (Geography) and for wood anatomy at the University of Basel (Botany). Once a year he is also teaching an international course on wood anatomy.