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Tree Rings in Archaeology, Climatology and Ecology

Volume 12

Proceedings of the DENDROSYMPOSIUM 2013
May 8th – 11th, 2013 in
Viterbo, Italy

Edited by:
Alfredo Di Filippo, Gianluca Piovesan,
Manuela Romagnoli, Gerhard Helle
and Holger Gärtner

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Preface

This publication is a result of the 12th TRACE conference (Tree Rings in Archaeology, Climatology and Ecology) organized by the Department of Agriculture, Forests, Nature and Energy (DAFNE) of the Università della Tuscia (Viterbo, Italy) on May 08th – 11th 2013 in Viterbo, Italy.

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. The annual conference provides a scientific platform for young scientists at high level.

More than 100 scientists working on tree-ring related topics participated in the conference coming from Belgium, Bolivia, Canada, Czech Republic, France, Germany, Israel, Italy, the Netherlands, Poland, Slovenia, Spain, Switzerland and Turkey.

The participants enjoyed about 80 presentations, divided almost equally between talks and posters, organized into five scientific sessions: "Global change and forest dynamics", "Wood anatomy and dendrochemistry in plant biology", "Dendroecology, dendroclimatology and forest management", "Frontiers in tree-ring science: new species and methodological approaches", "Cultural heritage and environmental history".

A total of 20 manuscripts were submitted. After review 19 short papers are published in this volume, giving an overview of the wide spectrum of fields in tree-ring research. We would like to thank the authors for contributing to this TRACE volume, and the reviewers for their valuable comments on the manuscripts. The organizers of the conference also wish to thank for their financial support the sponsors of TRACE 2013:

Beta Analytic Ltd. (United Kingdom), Ecomatik, (Germany), Fondazione Anna Maria Catalano (Italy), Häglof, (Sweden), Regent Instruments Inc. (Canada), Rinntech (Germany).

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SECTION 1

ARCHAEOLOGY

Dendrotypology as a key approach of former woodland and settlement developments. Examples from the prehistoric pile dwellings on Lake Constance (Germany)

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Introduction

With its well differentiated hill landscape largely covered by the forests in former times, the Circum-Alpine foreland represents an area of major interest for the study of the interferences between human settlement activities and environmental changes. This is a central task of the pile-dwelling research, which experienced a revival in the region from the 1970s onward, culminating with the *prehistoric pile dwellings around the Alps* beings added to the UNESCO's World Heritage List in 2011 (Suter & Schlichtherle 2009). Under this flag, two main aspects have been enhanced for the coordination of new conservation and investigation projects, namely common trends and regional patterns of the pile-dwellings phenomenon. Both aspects are also cores of the dendroarchaeological task, which played a key role in the archaeological development there. They are detailed in a new paper presenting the stand of dendrochronology in pile-dwelling research in North Italy, Slovenia and SW Germany (Martinelli et al. in press). With examples from the last named region, the present paper is designed to the second aspect, which can be particularly well highlighted by means of dendrotypology.

Dendrotypology, design and working space

Dendrotypology has been developed as an attempt to sort timber in relation to wood anatomy, tree-ring analysis and techno-morphology (see Billamboz 2011 for a more precise definition). Grouping tree-ring series according to cambial age and growth trend allows a better control in chronology building as well as in tentative dating young wood, which is frequently found in wetland archaeology. At the same time, dendrotypology is a basic tool in the reconstruction of building history, especially in the detection of house foundations within dense post fields resulting from repeated building activities in the same place through time. This is particularly the case of the Neolithic pile dwellings, where timber supply is assumed to have been conducted at household level without redistribution of converted wood within the community. Furthermore, sorting the series in dendro-groups allows an insight in the age structure of the exploited stands, and, on this basis, dendrotypological models of woodland management have been defined, especially concerning the historical woodland practices (Billamboz 2011). From this perspective, dendro-groups are considered as basic units of a multiple approach addressing the technological and social, as well as economical and ecological aspects of settlement development and woodland use.

According to the high proportion of young wood in the numerous sample series provided by large-scale scale excavations in pile dwellings, dendrotypology involves more largely visual matching than standard dendrochronology. Growth characteristics reflecting stand dynamics, human activities, and climatic or biotic effects are observed on raw, non-detrended tree-ring series, and are retained as cross dating markers. However, for consistency and reliability of the results, dating strategies operate at three distinct levels. Level A: independent dating with standard methods of dendrochronology; level B: context-dependent dating with external support by other methods; and level C: dating simulation considered as a first proposal. Only dating results at level A and B are suitable for publication, whereas level C is at present reserved for internal evaluations and discussions with the partners directly concerned. Consequently, longer consistent chronologies underlining the development of mature stands at local and regional scale are principally

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established on A-dated series, whereas the combination of B-dated series is aimed towards the definition of shorter sub-chronologies, reflecting stand dynamics of young forests or understorey structures. In Hemmenhofen, the working space designed to dendrotypology (“atelier dendrotypologique”) is distributed on two connected PC’s with following units:

- a laboratory dendro-package (Visual Basic) connected to a databank system (one databank per site for the large timber series and a general one embracing the smaller datasets). The common data structure is based on the data distribution in two main tables: table AD embracing the archaeological information generated on site during the excavation as well as the wood-technological and dendrological one (first operation in the tree-ring laboratory: techno-morphological documentation of wood samples or even whole timber, anatomical determination of wood-species, further dendrological characteristics); table DC for the tree-ring analysis, measurements and dendrotypology.

Among others possibilities of evaluation, one can note the SQL-based query facilities for the dendrotypological assemblages as well as for systematic correlations between individual series, dendro-groups, and local and regional chronologies.

- visual matching on graphical interface (COREL Draw with curve display on respective layers, sample number automatically transferred as label of layer in the first curve process. The sample label appears automatically by clicking on the curve. Each curve is presented as a closed drawing object with the help of a horizontal line between the first and the last ring value. This line corresponds to the 0,1mm tree-ring width value, allowing a direct comparison of the growth rate and trend of the series to be assembled.
- control of the dendrotypological process on the map (CAD). As far as possible, dendro-groups are constructed in relation to the archaeological structures. In this way, they can be used as basic units acting, as shown in the following chapter, as interface between archaeology and forest sciences.

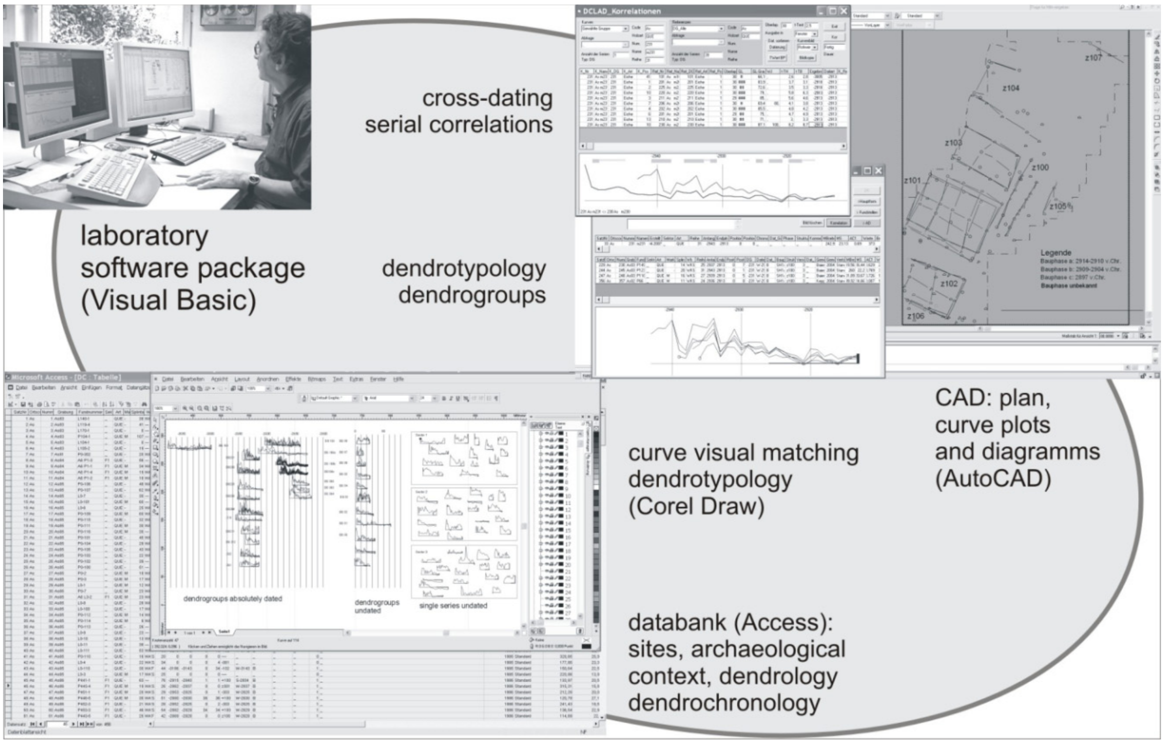

Figure1: Working with two parallel computers in the “atelier dendrotypologique” at Hemmenhofen. For the needs of dendrotypology applied to large sample sets, a software package has been developed, allowing tree-ring analysis of short tree-ring sequences, data transfer and handling in databanks as well as data output via graphical interfaces. Registered trademarks are Access and Visual Basic (Microsoft Corporation), Corel Draw (Corel Corporation), AutoCAD (Autodesk, Inc.)

Applied dendrotypology in Sipplingen: lake-shore occupations in the bay, woodland development in the hinterland

Previous work has already illustrated this kind of interferences. In the village of Hornstaad-Hörnle IB (Billamboz 2006) for instance, the strong demographic expansion during the intermediate phases of occupation is directly linked to the intensive oak coppice practices, whereas the reduction of the building activity at the end indicates the use of old trees as markers of thinned woodland. Such development can be followed on a larger scale of time, especially in the bay of Sipplingen (Billamboz et al. 2010), where several waves of lake-shore occupation between 4000 and 2400 BC could be highlighted by systematic tree-ring dating (3784 oak samples analyzed) and means of dendrotypology (fig. 2). With amphitheater-like settings enclosed in geological faults and offering several vegetation belts over a gradient of 200m, the hinterland offers very suitable conditions for this approach. A first complete cycle of woodland use can be followed over 250 years between 3860 and 3650 BC. It begins with clearing activities in dense oak mixed stands during SiB-C. In the intermediate phase (SiD1), expanding building activities are linked to extensive coppice practices. This development finds an abrupt end around 3650 BC (SiE), here again the strong reduction of the building area is characterized by the use of old trees. The replication of the same cycle in the neighboring villages of Bodman and Ludwigshafen underlines the common character of this development, limited, probably at small scale, by coppice aging and woodland degradation. Comparing the distribution of dendro-dates between Obersee and Untersee in the following period, observations converge towards an interpretation of settlement relocation. It is possible that land overuse led to a loss of attractiveness in the first region, whereas the second one, with its more structured landscape, presented better possibilities for various and more sustainable subsistence strategies at the beginning of the climate degradation of Piora II.

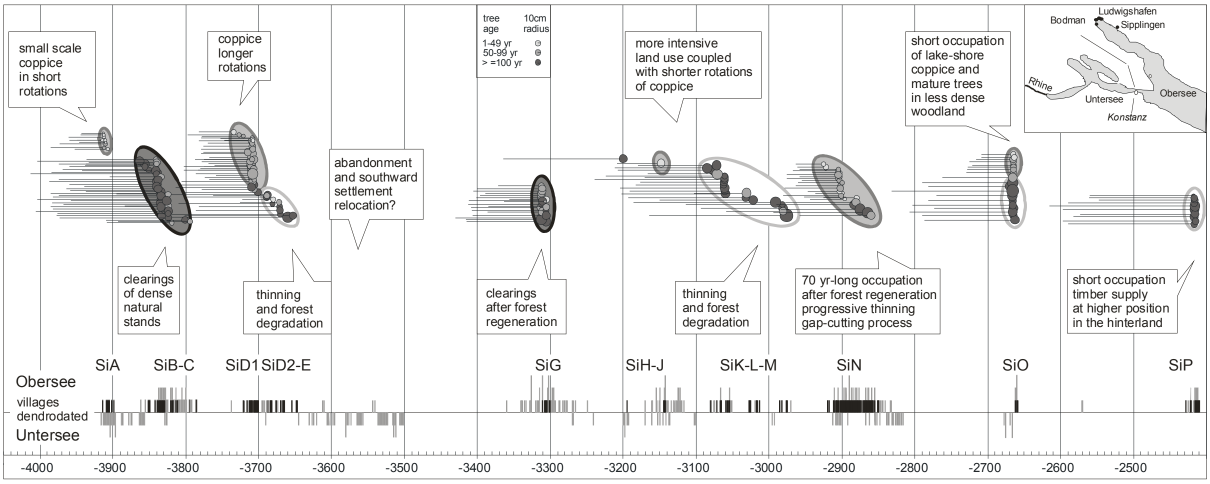

Figure 2: Dendrotypology applied to the oak timber series from the Neolithic pile dwellings of Sipplingen at Lake Constance. Dendro-groups are represented as bar (approx. tree age) and circle (mean stem circumference).Their assemblages allow to outline the structure of the exploited stands during the course of repeated occupations on the shore between 3920 and 2400 BC (building phases SiA-P in black in the diagram below). Common trends and shifts of the lake shore occupation in both parts of the lake seem to be linked to the state and development of the surrounding woodlands and subsequently this allows define regional patterns of settlement and woodland development (further explanation in the text).

After woodland regeneration, a second similar exploitation cycle is to be followed in Sipplingen from clearings in SiG to the final thinning in SiL-M, whereas coppice practices based on shorter rotations and more intensive woodland use are of less evidence in the intermediate phases SiH-J-K. Shortly after 3000 BC, forest regenerated again for the needs of an intense occupation (SiN), showing the building of several parallel footbridge-like villages with continuous repairs over 70 years. Landscape opening is attested at the time by archaeobotanical findings. The two last occupations SiO and SiP, belonging to the Corded Ware Culture are very short in time. According to anatomical features and absent growth trend it could be assumed that oak timber supply in the last phase did not occur at lower slope position behind the settlement, but much more at higher one, where nowadays *Quercus petraea* is still growing. Considering these conditions and the poor evidence of the occupation, restricted at that time at the shore portion between Ludwigshafen and Sipplingen, it seems that dendrotypology may offer new elements for an interpretation of an ecological collapse at the end of the Neolithic pile dwellings at Lake Constance.

The development roughly presented here can be shown in more detail through the implementation of dendrotypology. Further parameters such as pointer years or abrupt growth changes (Bleicher 2009) could be highlighted, giving for instance a better insight into the timing of coppice rotations. Ecological parameters as the cockchafer signal (negative effect on oak tree-ring formation according to the cycle of reproduction) are also taken in account (Billamboz 2014). Synchronous flight years of the common cockchafer *Melolontha melolontha* L. could be derived from the series of old-aged oaks in Bodman and Sipplingen, and from young poles in Hornstaad-Hörnle just before the first occupation SiA. Beyond dating facilities, this marker can also be used for ecological evaluations. The significant demographic development during the phase SiN is also accompanied by cockchafer outbreaks around 2900 BC, probably in relation with increasing clearing activities, which, themselves, could have fostered the development of the cockchafer populations.

A particular aspect of the study concerns the relocation of the timber sources according to the altitudinal gradient of the hinterland and its vegetation belts. Two main tendencies can be outlined; with a more general one relating to the exploitation of oak mixed stands at lower position near to the settlement. High growth rate in the juvenile phase and strong negative grow trend are characteristic of pedunculate oak (*Quercus robur* L.), which was the main tree-species in this area, embracing the upper part of the riparian forest and the adjacent lower slopes. Additive sapwood investigations, as done elsewhere on dendroecological oak coppice studies (Girardclos et al. 2012) allow assessing the stand density in the rythmes of the forest regeneration and exploitation (sapwood index = sapwood width in 1/100 mm / number of sapwood rings). Old-aged oaks taken from dense stands for the building of the settlement SiB show a thin sapwood area, attesting (because of the numerous rings) a slow duramenisation under high degree of competition and reduced light conditions. Opposite patterns are to be found during the course of the exploitation cycles showing enlarged sapwood area coupled with accelerated duramenisation. It seems that an increase in clearing activities in phases of demographical expansion lead to the relocation of the timber supply at higher position. This second tendency has been already mentioned in the case of the final occupation SiP, characterised by the use of old-aged and slowly grown sessile oak trees. This first interpretation based on tree-ring width investigations should be checked by additive parameters. For a better differentiation between both oak species in contrasting site conditions, wood vessel analysis of archaeological and recent material is in preparation (S. Million in cooperation with P. Fonti and G. von Arx, WSL Birmensdorf).

Conclusion

With the example presented here, dendrotypology seems to be a suited approach to highlight the interferences between woodland and settlement developments, under consideration of both aspects of natural evolution and historical discontinuities. The strength of the method is based on contextuality and multiscalarity. With climatic and cultural evolution as background on a multi-centennial scale, it is possible to follow shorter developments, coupled with demographic fluctuations and settlement relocations within generations. Or, even more detailed accounts, concerning the building history of each house unit, as indicated by piles added to the initial foundation.

The application of dendrotypology on many aspects of cultural and environmental archaeology offers large possibilities for trans-disciplinary research, and has been adopted as a reference in the project Sipplingen. The results presented here show clearly that ecological aspects should be taken into account more often in pile-dwelling research that focuses in particular on the settlement response to the climate evolution and the subsequent lake-level fluctuations. From a wider point of view, new orientations linking e.g. historical ecology to forest sciences (Dupouey et al. 2002), or modeling stand dynamics (Rameau 1999) are welcome, and dendrotypology has already been used to identify characteristic tree growth patterns (Bleicher 2013). All this should lead to a better understanding of past woodland and settlement developments North and South of the Alps. Within this scope, it may be possible to underline the questions concerning the regional adaptations of coppice, which plays a major role in woodland management in former times.

In the same way, dendrotypology could link both climatological and ecological streams of tree-ring research beyond dating. For example, the building of sub-chronologies in relation to the question of divergence in climatic reconstructions is indeed a kind of dendrotypology. Consequently, future research outlooks should consider a closer involvement of dendrotypology in the evaluation of archaeological tree-ring data from a climatological perspective. Finally, dendrotypology can also be used as reference for the combination of parallel analysis (e.g. sample choice in dendro-chemistry) – in some cases even for selective sample curation.

At least, a personal comment: with respect to its wide-ranging information potential at the interface between humanology and natural sciences, dendrotypology was a permanent motivation in the daily laboratory work over more than 30 years. My response to questions about related methodology and transfer of knowledge would be: dendrotypology is not a simple method, but much more a kind of approach basing on a bundle of methods and combination of parameters. This approach had still until now an empiric character, and methodological improvements could be probably made through a nearer cooperation between dendroarchaeology and forest sciences, particularly on the concern of the structural changes of woodland in the past. For teaching and learning, laboratory training as done in dendroecological or wood-anatomical field-weeks could be a first solution, leading to a better integration of dentrotypology in dendroarchaeology and other fields of research. Dendrotypology bridging dendroarchaeology and forest ecology through times? A new challenge for young researchers.

Acknowledgements

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The “Master Of Elsloo”: An anonymous Production of Sculptures documented by Dendrochronology

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Introduction

In 2010-2011, the Royal Institute for Cultural Heritage (KIK-IRPA) was part of an art-historical, technical and archival international research project dedicated to the late medieval sculptor called ‘Master of Elsloo’ (Peters 2013).[*] An important production – more than 200 sculptures – was attributed to this anonymous master on the basis of stylistic similarities with the eponym sculpture conserved in Elsloo, a small town in the Dutch Limburg (Te Peol 2007). Objectives of the project were to describe this production in terms of style and technique, considering the possible intervention of different workshops, and to specify the so-called ‘Elsloo style’ from other contemporaneous productions (Fig. 1). Within this framework, the tree-ring study of most of the sculptures conserved in Belgium, all made of oak (*Quercus* sp.), had different aims: to contribute chronological data to this production located quite far from the well-known artistic production centres from the Southern Netherlands, to characterise the wood used and to provide information on its geographic provenance. This paper summarises the information collected from this tree-ring research.[†]

Fig. 1a Fig. 1b Fig. 1c Fig. 1d

Figure 1: Sculptures attributed to the ‘Elsloo group’: Fig. 1a: St Lucy, Siersdorf, Church of St John the Baptist, detail; Fig. 1b: St Anne with the Virgin and Child, Sint-Truiden, Provinciaal Museum Begijnhofkerk, inv. ST/90/001; Fig. 1c-d: St John the Baptist, Siersdorf, Church of St John the Baptist, front and detail. © KIK-IRPA

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[*] Results of this interdisciplinary project were presented at the conference *A Masterly Hand. Interdisciplinary Research on the Late-Medieval Sculptor Master of Elsloo in an International Perspective* organised by the KIK-IRPA in October 2011; the proceedings of this conference will be published soon (Peters 2013).

[†] The results of this study are presented in more details in Fraiture (2013b).

Material and methods

Fifty-two sculptures were retained for dendrochronological research, mostly conserved in Belgium, with some in the Netherlands and Germany. All the sculptures analysed are made of a single piece of oak, *Quercus robur* or *Q. petreae*. This systematic choice of oak may be surprising, for other species are softer and easier to carve. Oak was considered to be of superior quality; it had been the most commonly wood species used for works of art since the Carolingian period in north-western Europe (Lavier & Lambert 1996), particularly in the Southern Netherlands (Verougstraete & Van Schoute 1989, Fraiture 2009b, Haneca et al. 2005).

Several sculptures were made of fast growing trees.[‡] Yet the faster the growth, the denser and the harder the wood, making it more difficult to be sculpted. Knots also make carving more arduous, but these are very common. Observation of these statues tends thus to show that the selection of the log was not made on the most easily worked material but on its suitability to the planned sculpture in terms of shape and dimensions. This is well illustrated by groups carved from a bifurcating section of trunk (Fig. 1b), apostles with attributes carved from knots or other figures intentionally sculpted from elongated trunks. That the sculptor sought the shape of his future statue in the tree he selected might indicate that the material was fully exploited.

Methodologically, dendrochronological analysis of works of art needs to be conducted in a non-destructive manner, without destructive sampling. To achieve this ambitious two-year project, most of the works had to be examined *in situ* (in churches for most of them), given temporal and financial imperatives.[§] In these conditions, the equipment had to be movable; no recourse to scientific imagery such as tomography could thus be applied (Bill et al. 2012). Tree rings had to be measured directly on the base of the object, which corresponds to the transverse section of a trunk. Analysis of figures that do not have flat bases such as Crucified Christ had thus to be rejected. On other sculptures the wood itself did not permit analysis, either being too degraded or having large growth distortions.When the wood on the base is irregular or the growth is quite slow, minor preparation with a brush and/or a blade is done along one or several radii. The ring series are recorded using macro-photographs calibrated by a millimetric scale and the ring widths are measured on the computer screen with an accuracy of 0.01 mm. The measurement itself is performed by a specific procedure in *Adobe™ Photoshop™*; the data is then converted to 'Besançon' format.[**] Comparisons between ring series and assemblages of mean chronologies, by drawing and by computing, as well as the dating calculations are carried out using the *Dendron IV* software,[††] after calibration of the dendrochronological series by a 'corridor' transformation (Lambert 2006). The reference database used for the project comprises several categories of data, provided by different European laboratories.[‡‡] *Master* or *regional* chronologies are each representative of a more or less extensive geographical zone. *Site* or *local* chronologies come from the same building phase or archaeological site. Finally *individual* chronologies, taken from different types of materials – archaeological, architectural, artistic – each represents a single tree.

A major difficulty in the dendrochronological examination of the Elsloo sculptures is the limited number of rings on many of them. This is due to the fact that several works were sculpted from fairly young trees and that large sculptures have been hollowed to avoid cracking and distortion of the wood during drying, reducing the measurable length of the ring series. However, typically, to provide an unequivocal result, a minimum of 70 to 80 rings is needed for a single piece of wood (Hillam et al. 1987). In the Elsloo group, the ring series contain between 19 and 120 rings. Twenty-four sequences – almost half – have fewer than 70 rings; of these, 13 have fewer than 50 rings. As this group of

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[‡] Some statues show rings wider than 4 mm of growth in an average year.

[§] Only 3 sculptures were moved to the KIK-IRPA restoration studios, in order to dispose of the specific equipment to study their original polychromy (Peters 2013).

[**] The measurement procedure has been developed by G.-N. Lambert (G.-N. Lambert, KIK-IRPA, unpublished), creator of the 'Besançon format' (Lambert & Maurice 1992).

[††] *Dendron IV* is unpublished (G.-N. Lambert, University of Liège).

[‡‡] See note 10 and acknowledgements for the contributors.

sculptures is more or less consistent in terms of period and region, their tree-ring series could be compared and assembled, providing longer chronologies than the individual series (Schweingrüber 1988, Trénard 1992). The success of the results for this project is thus to a great extent due to the large number of sculptures that could be analysed.

Results

Elsloo sculptures made from the same log

In this consistent group, it is not surprising that several statues are made from the same log. Identification of sculptures coming from the same tree is based on several criteria (Fraiture 2009a, Beuting 2011, Fraiture in press): *t*-values, quality of graphs of the raw ring widths, mean ring widths, dates of first and last rings, macroscopic anatomical characteristics. Examples of statues originated from a single log have been met particularly for iconographic ensembles such as series of apostles: small sculptures are carved either from quarters of a trunk, or from boxed heart sections of young trees or thick branches. Other statues originating from the same tree appear in different sub-groups of figures, providing additional arguments in favour of the homogeneity of the production and supporting the stylistic similarities noticed between some of them (Peters & Cattersel 2013).

Dating of the Elsloo Sculptures

Despite the expected difficulties, of the 52 sculptures analysed, 29 could be dated with certainty (Fig. 2). Among the undated statues, half have fewer than 70 rings or even fewer than 50, while several others have obvious growth distortions or show complacency. In such conditions, the successful dating of nearly 60% of the sculptures is rather exceptional. In brief, the dates of the last rings measured range between 1479 and 1513. Such results must be interpreted in function of the wood removed while preparing and carving, and the lapse of time between the felling of the tree and the use of its wood.

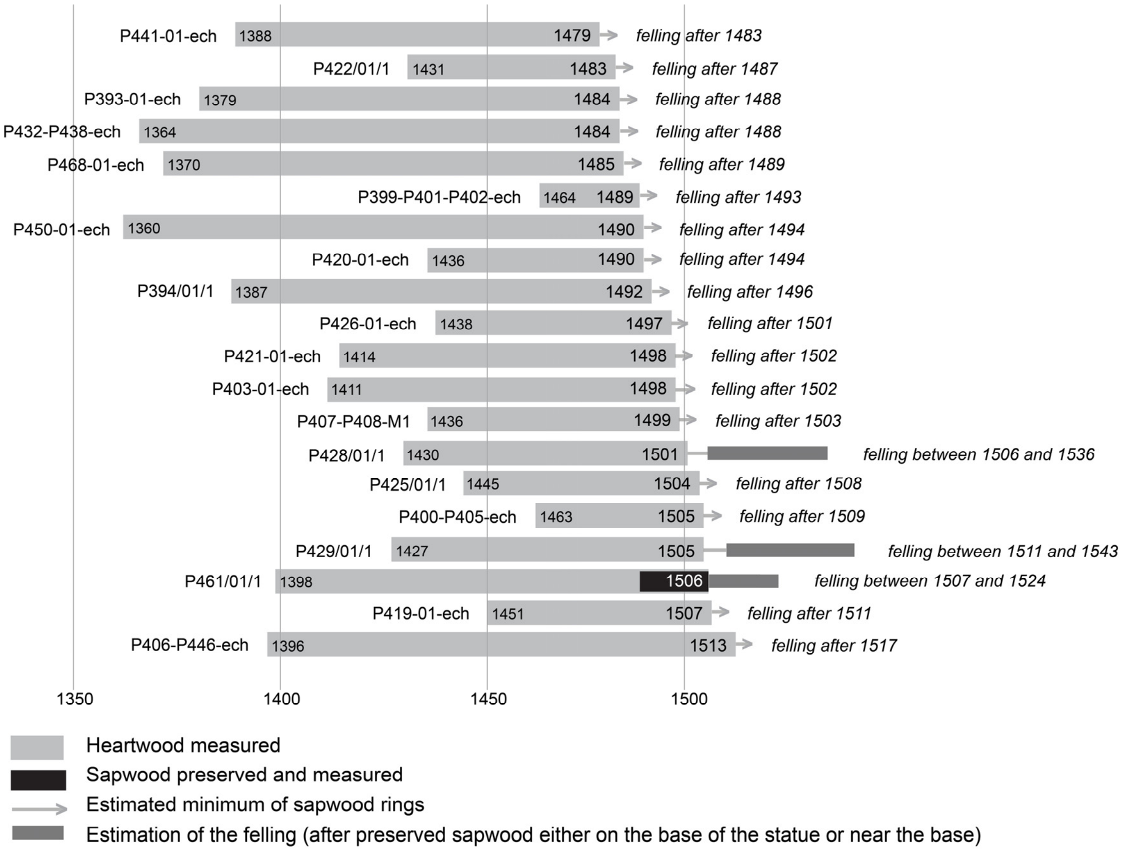

Figure 2: Bar diagram for the 26 dated series (from 29 sculptures: one series for statues from the same log).

The complete sapwood up to the cambium – leading to a felling date to the year – has never been met in the Elsloo project. The fragile sapwood is unsuitable for sculptures because it affects their durability. Yet sometimes part of it remains. The number of missing sapwood rings could thus be estimated within a range based on statistics recorded on trees of comparable age and provenance (Hollstein 1978). Unfortunately, very few Elsloo statues preserve sapwood in their narrower base: when sapwood is partially preserved, it is generally visible on the figures' elbows, where the sculpture's width is maximal. These remains are thus unsuitable for specifying the felling date because they are too far from the ring series on the base to be linked to these. For two cases, however, sapwood was present very close to the base allowing the estimation of the felling date to a few years for these statues, and another exception includes 17 sapwood rings on its base (Fig. 2).[§§]
These sapwood remains, even if they are not always usable for dating, nonetheless provide key information: they indicate that the wood was exploited to the full, with only the absolute minimum being removed and even then not always entirely. This idea is further supported by the aforementioned observation that the shape of the trunk was retained in the contour of the carved figure. From a dendrochronological viewpoint, this economical use of the wood indicates that the loss of rings may well be minimal, especially in the case of large works or statues of a particular shape. A total absence of sapwood represents, however, the situation most commonly encountered. In these cases, there is no way of determining the number of heartwood rings lost in addition to the sapwood: the date of the last ring measured represents a *terminus post quem* for felling, a date after which the tree was felled. Anyhow, as each oak has a minimum number of sapwood rings, this minimum can be systematically added to the last heartwood ring measured to slightly advance the result to the felling date (Fig. 2). This result remains a *terminus post quem*, however, because the amount of heartwood lost is still unknown.

The second unknown factor to take into account when estimating the statue's production date is the lapse of time between the felling of the tree and the use of its wood. This point is important to discuss, in order to clear up some misconceptions about the seasoning of the wood. For carving, particularly in oak, the wood needs to be green because once dried it becomes difficult to cut against the grain, in particular to obtain delicate anatomical or clothing details (Fig. 1). This means that the sculptor had to work the wood before it had dried or seasoned. This is evidenced by sculptures in which drying cracks appeared after they were finished (Fig. 1d)[***] and by tool traces characteristic of working on fresh wood (Truyen, in press). This use of green wood implies that sculptures made from the same tree are contemporaneous: this information is of interest for art history, as dendrochronology has revealed several pairs of statues in the Elsloo group that derived from the same log.

Bearing all this information in mind and on the basis of the dendrochronological dates for the sculptures dated with certainty, it can be concluded that all Elsloo statues could have been carved between the late 15th century (1483 at the earliest) and the mid-16th century (Fig. 2). This range is the broadest possible. It is calculated on the basis of minimum sapwood for the *terminus post quem* of 1483 and maximal sapwood for the *terminus ante quem* of around 1550, by considering that the amount of lost heartwood rings is minimal, and taking into account a negligible lapse of time between felling and use. These variables account for the length of the given interval and they make it impossible to establish a relative chronology between the works based solely on dendrochronology.

Provenance

Dendro-provenancing is a relevant approach for the reconstruction of trade networks. It can help to better determine where and how craftsmen were supplied with raw material. In the study of the Elsloo sculptures, the first step was to compare the tree-ring series from the dated statues in order to

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[§§] For the Elsloo sculptures, the number of sapwood rings is estimated according to Durost and Lambert 2007 (4-34 rings).

[***] Ian Tyers, during the conference *A Masterly Hand…* (21 Oct. 2011), showed the biological necessity for using green wood, and supported this with many examples both in the Elsloo group and outside it.

determine groupings from a dendrochronological viewpoint, assuming that these groupings have a geographic significance (Hillam & Tyers 1995, Fraiture 2009b). Using square correlation matrices of *t*-values, three clusters have been identified (Fig. 3). It must be noted that they are not entirely independent from one another as they show high correlations between series from different clusters, indicating probable geographic links between them.

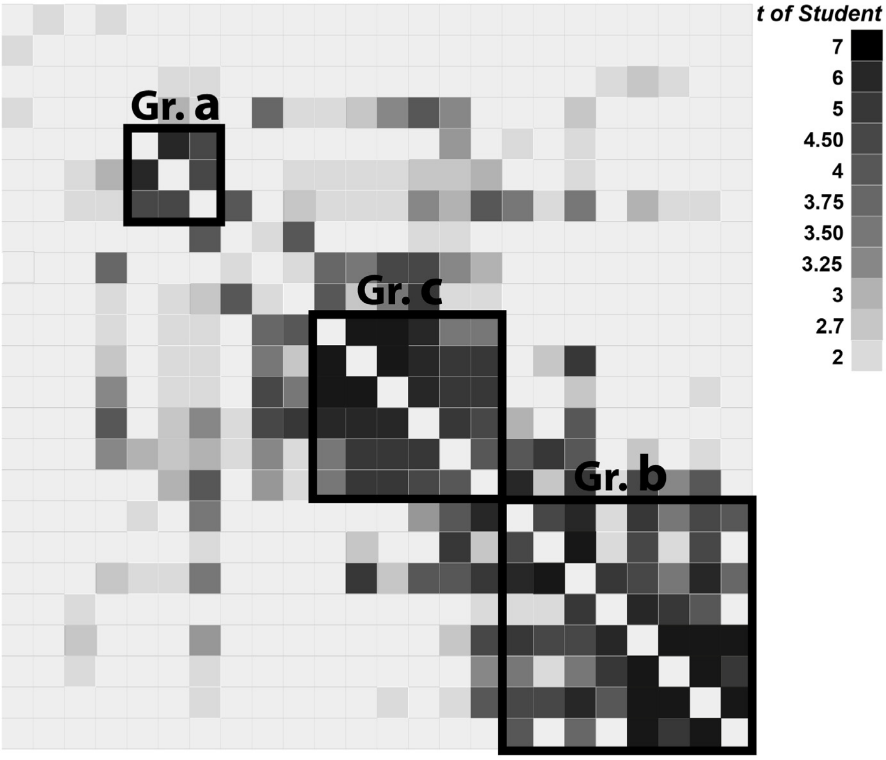

Figure 3: Square correlation matrix showing three distinct clusters: groups a, b, c.

The smallest group (group *a*), top left in the correlation matrix (Fig. 3), is composed of four figures from a series of 'apostles and Christ' and a fifth sculpture which is from the same log as the Christ (the five statues comig from three distinct trees). The largest (group *b*), bottom right in the matrix, includes ten apostles from two series of figures. The third (group *c*), seen in the middle, includes sculptures from different iconographic ensembles, among which some differ in style. This last observation is important since this research confirms the geographic coherence of these sculptures. In other words, dendrochronology, rather than dissociating groups of statues, tends to bring them even closer.

In order to determine the geographic provenance itself, the dated ring series of the Elsloo sculptures were firstly compared with master chronologies from western Europe and the results were mapped (Fig. 4a).[†††] There is evidence that the wood sculpted is of local origin, that is, largely the region where the Elsloo statues must have been produced.[‡‡‡]

[†††] Published regional chronologies used: Becker 1981, Delorme 1973, Hollstein 1965, Hollstein 1980, Pilcher 1987. Unpublished regional chronologies used: Arden4 (1993), Liege3 (1993), Namur2 (2005), Meuse5 (1993): ULg/CEA: Hoffsummer *et al.* (see Hoffsummer 1995); NLZuidmm (2005): Stichting RING: Jansma *et al.* (see Jansma 1995); Münsterland (2011), Maastricht (2011): Pressler GmbH; Lorraine (2005), F-NordEst (2005), F-Meuse (2005): DendroNet, Tegel; Koeln04 (2011): Universität zu Köln, Schmidt; Westphalie-Hellwegzone (1991), Niedersächsischer Küstenraum (1979): Universität zu Hamburg: Eckstein *et al*.

[‡‡‡] Baltic oak was systematically used for sculpted altarpieces in the Southern Netherlands (Haneca et al 2005, Fraiture 2013a). It was not the case for sculptures in the round because the imported Baltic semi-finished products (Bonde et al. 1997, Salzman 1979, Tossavainen 1994, Wazny 2005, Zunde 1998-99) did not correspond in sizes and shapes to the material needed for this kind of statues (Fraiture 2000).

To narrow down this broad provenance zone(s), site chronologies from Belgium, France, Germany and the Netherlands have been used (Fraiture 2009b), which cover as completely as possible the overall zone(s) of presumed origin shown in Fig. 4a. The results were mapped to visualise the sub-regions offering the strongest dendrochronological similarities with the sculptures (Fig. 4b-c-d).

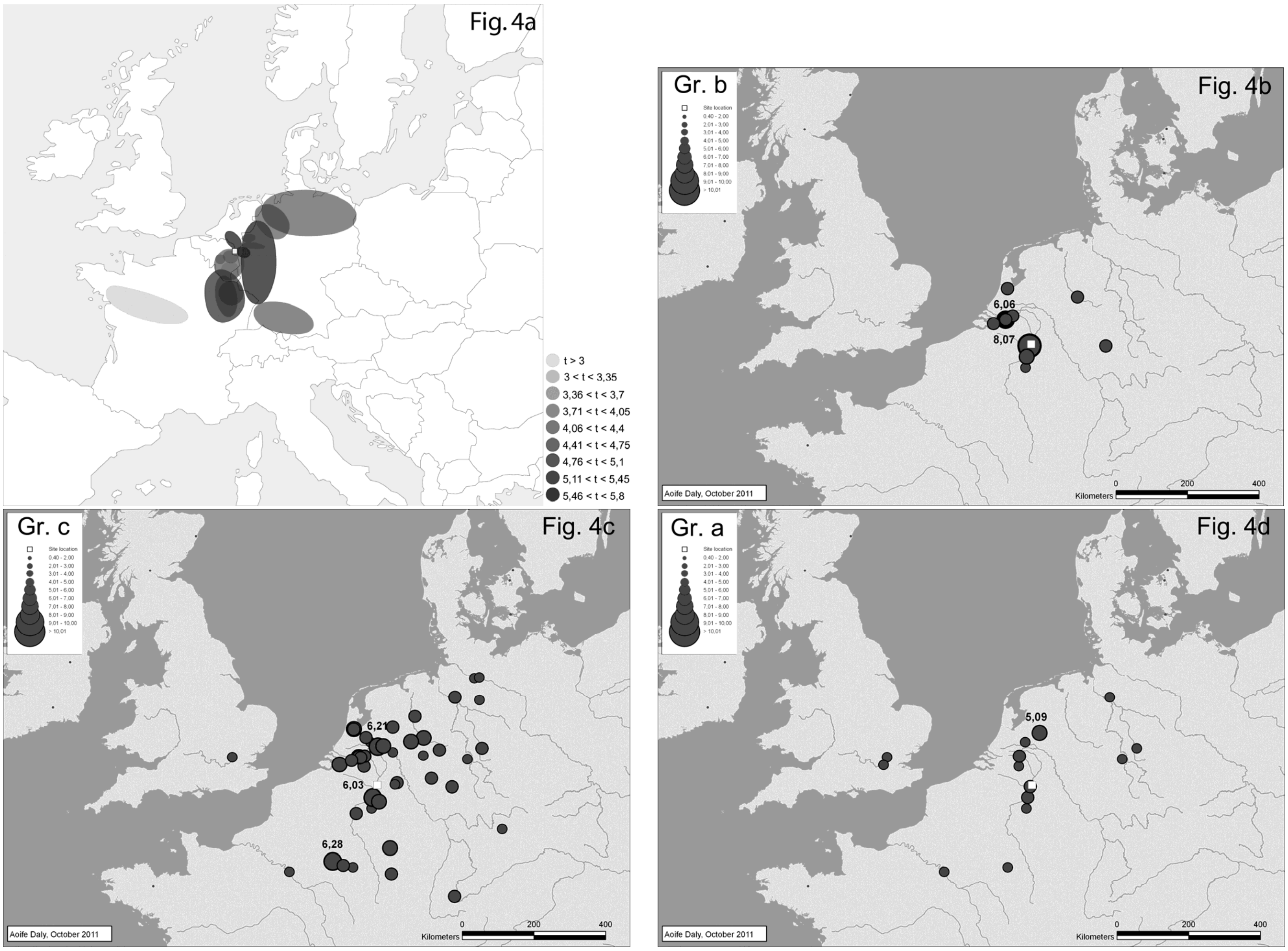

Figure 4a: Map showing the quality of the correlations between the dated ring series from the Elsloo sculptures and master chronologies from western Europe (the darker the dots, the better the correlations); Figures 4b-c-d: Maps showing the quality of the correlations between the three groups of Elsloo statues and site chronologies from western Europe (the bigger the dots, the better the correlations).

The group *b* (Fig. 4b) seems to show the strongest similarities with chronologies from the Maastricht region and with chronologies from the region downriver from Maastricht, near the Rhine-Meuse-Scheldt delta. It must be noted that the chronologies from this latter region do not reflect a provenance from this area because they include ring series that come from imported timbers, probably from the Meuse basin (Jansma 1995).[§§§] Nor is it possible to ensure that the ring series included in Maastricht site chronologies actually come from this region, since the nearby Meuse was an important timber transportation route at the time. So the use of imported oak – from remote private or state forests, for example – for the construction of prestigious buildings cannot be excluded. Nevertheless, the fact that no other zones (such as the Ardennes) show significant correlation rates seems to argue for the use of oaks felled in the region of Maastricht. This is

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[§§§] The probable provenance zone(s) for these woods were firstly thought to be the Meuse basin and/or northern or central Germany (Jansma 1995). A current research tends to circumscribe them to the solely Meuse basin (Jansma et al., in preparation. The provenance of oak and pine timber used in north-western Europe during the 16th and 17th centuries: a dendrochronological reassessment using the DCCD repository and the TRiDaS Data Standard; see Jansma et al. 2012a, Jansma et al. 2012b; http://dendro.dans.knaw.nl).

consistent with the findings of the archival research carried out recently showing the contemporary exploitation of forests close to Roermond, a town located on the River Meuse less than 50 kilometres from Maastricht.[****] These results could mean that this group *b* was sculpted in wood coming from the forested vicinity of the workshop(s), wherever their precise location is likely to have been.

The group *c* provides more complex results to interpret (Fig. 4c). Significant *t-values* are given by chronologies from many different regions, with the best results obtained by chronologies from the southern part of the modern Netherlands (North Brabant, Gelderland), the Meuse upstream from Maastricht (in modern Belgium and France), and along the River Ems along the border between the modern Netherlands and Germany (Lower Saxony up to North Rhine-Westphalia). Here again however, the chronologies from the southern part of the modern Netherlands include ring series from wood imported from the Meuse basin. Considering the fact that, unlike the previous group, no high correlations were given with sites chronologies from the Maastricht region, the oaks used for these Elsloo sculptures might have been imported. Examination of the map tend to show that these oaks were imported either from the Meuse basin upstream from Maastricht, further south, or from Lower Saxony or North Rhine-Westphalia, further north, without being more precise.[††††]

The small group *a* does not allow precision of the provenance because the correlation rates are not high or contrasting enough to specify one region rather than another (Fig. 4d). This is also the case for most of the dated sculptures that were not included in one of these three clusters. Nonetheless, the trees used for the group *a* also seem to come either from the Meuse or the Moselle basins upstream from Maastricht or from North Rhine-Westphalia. Difficulties in determining the provenance of the oaks used in these statues result from the same factors that complicated the process of dating: the complacency of most of the ring series weakens their dendrochronological signal.

It is known that craftsmen could find several kinds of timbers of different sizes, shapes and species in the wood markets, as is shown by the use of different terms in archival documents.[‡‡‡‡] It remains difficult, however, to find out what kind of timbers some of these terms actually refer to and thus to know precisely which products would have been available to sculptors on the market. It would be interesting to know whether bifurcated trunks, for example, were amongst the products transported on the Meuse in the late Middle Ages.[§§§§] If not, was the sculptor obliged to prospect by himself in the forest? Indeed, given the observation that material selection was made according to the shape and size of the trunk, it is possible that the sculptors made their choice directly in the forest, as craftsmen did for very special pieces intended for building and shipbuilding[*****] and as some artists still do today.

The new information regarding the use of timbers potentially imported over quite long distances for some Elsloo statues lead us to consider the possibility of their transport by rafting along rivers,[†††††] as it is documented for the Meuse at that time (Fanchamps 1966). This possibility could contradict our interpretation of a rapid use of the wood after felling because the wood would stay fresh during transport and potential storage in the water. However, in such a context, it seems to us unlikely that logs destined to be carved could have been transported to sculptors' workshops via this method,

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[****] Correspondence with Gerard Venner (25 Sept. 2012) and discussions during the conference *A Masterly Hand...*

[††††] It should be noted that the network of site chronologies does not equally cover the entire probable provenance area of the oaks used, in particular in Germany (few laboratories work daily with site chronologies). Consequently, the lack of good correlations in a given region, for example upstream in the Rhine basin, does not necessarily mean that the oaks do not come from this region. Conversely, good correlations with site chronologies from a particular place indicate that the trees apparently have a quite similar response to climate than those of that area, without it being certain that they come from that area and not a neighbouring one for which there are no site chronologies. Lambert and Lavier 1997; Fraiture 2009b.

[‡‡‡‡] Such as *waynscot*, clapboard, deal, planks, staves for casks and pipes, oars, masts, shovels, chests for building, shipbuilding, furniture, barrels to mention but a few (Tossavainen 1994).

[§§§§] Seventeen different products were recorded at the time: 'navées de futaille, jantes, rabots, baches, bois de charlerie, core ou clippe-clappe, planches, barreaux, lattes […]' (Fanchamps 1966, Houbrechts 2008).

[*****] See, for example, Suger, *De consecratione* (3), cited and translated in Panofsky 1967; Duhamel du Monceau 1758, Penevert [around 1828].

[†††††] Question addressed by Ute Sass-Klaassen during the TRACE conference, 11 May 2013, Viterbo (Italy).

given the aesthetic value of the finished products and the irregular shape of some selected pieces, unsuitable for rafts.

Conclusion

The two-year project devoted to the study of the so-called ‘Master of Elsloo’ comprised the dendrochronological analysis of more than 50 sculptures. Difficulties in the tree-ring analysis itself were numerous, mainly due to the often poor dendrochronological quality of the trees used. Young, irregularly grown and often complacent, most do not contain a strong climatic signal. This led to 40% of the works remaining undated and to obstacles in the provenance research at a local level. Even so, the results presented in this paper represent a real achievement, which is due not only to the development of innovative dendrochronological tools and the extension of regional databases but also to the large number of sculptures that could be analysed.

Based on the tree-ring research, the Elsloo group can be dated between the late-15th century and the mid-16th century at the most recent. Significant variation in the number of sapwood rings from one tree to another precludes a more precise limitation of the period of activity, even though several indices reveal a maximal exploitation of the wood and an absence of seasoning time.

In terms of wood selection, most statues show a rather irregular growth, with many knots indicating the presence of branches low on the trunk, characteristics of trees that have grown in isolation or in open forest.

Three clusters have been dendrochronologically constructed. These include sculptures which belong to the same iconographic ensemble or not, sculptures which show strong stylistic similarities as well as others that differ in style. The high correlation rates between the ring series within these groups, which are interpreted as similarities in tree provenance, seem to suggest that if several workshops have been at work, they used the same procurement network(s).

Regarding these geographic provenances, different procurement zones have been distinguished. A group of figures proved to be sculpted from oaks from the Maastricht region. The map of the results given by a second group may suggest an imported supply, either likely somewhat upriver on the Meuse to the south (modern Belgium) or from North Rhine-Westphalia to the north. Finally, the data obtained for the smallest group are less explicit, but the wood seems also to have been procured from further afield.

The information acquired during this project, which is of different kinds and different degrees of precision, contributes to a better understanding of the context of production of these sculptures. It also raises new questions, particularly concerning procurement strategy of the workshops, which could be used to guide new historical research. It is now greatly hoped that such study will be continued, as more than 100 sculptures from the ‘Elsloo group’ preserved abroad are still awaiting dendrochronological analysis!

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Starting points for dendroarchaeology in Catalonia

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Introduction

Despite the fact that dendroarchaeology in Catalonia (Spain) has been a field somewhat neglected in comparison to other Mediterranean regions, nowadays there are the conditions for a relatively quick recover of such delay, thanks to mainly two factors. In the first place, the tradition of a series of fields complementary to dendroarchaeology has created a well established framework, which dendroarchaeologists could take advantage of: it's the case of dendroecological studies, that allowed the building of numerous chronologies from living trees (some of which are more than 600 years long, see Gutierrez et al 1998); pollen studies, that can reconstruct to some extent the ancient distribution of tree population from prehistory to recent times (Riera 2005; Miras et al 2007); and finally a series of localized studies about agriculture and tree culture in antiquity based on carpological data and plant remains (Buxò 2005).

In the second place, in Catalonia archaeology is a well integrated discipline in the development of urban planning and therefore a great quantity of archaeological digs are carried on. In this sense, it has to be noted that, even if from the point of view of climate conditions this territory is not among the most suitable ones for preserving organic material, wooden artifacts are being found more frequently in recent years. This is partly due to the fact that the so called "salvage archaeology" – that forms the immense majority of archaeological activity on the territory – deals with building activity, whose technological continuous improvement allows to always reach deeper strata. Here, the presence of the water table enhances the possibility of wood preservation, especially parts of wells, that, it has to be kept in mind, were one of the most common, because necessary, equipment in most of the historical settlements.

Previous dendroarchaeological experiences on the Catalan territory

Even if dendrochronological principles have been introduced from the archaeological point of view (Gutierrez 2008), until now the region suffers from a lack of professionals and the few cases of study were carried on by external laboratories.

The first and pioneering dendroarchaeological study was carried on La Draga Neolithic site, by Patrick Gassman at the Laboratory of Dendrochronology in Neuchatel (Switzerland), whose dig started in 1990 and is still on-going. Among hundreds of samples of oak wood, from rods and planks, dated by 14C to the sixth millennium B.C., some synchronized well to build a few floating chronologies (Gassman 2000).

We have to wait almost twenty years for a second dendroarchaeological experience: it concerned a shipwreck found in 2008, when a portion of the medieval port of Barcelona was archaeologically investigated. The construction technique, the analysis of the pollen contained in the sealing moss used in its construction and the investigation of the Late Medieval archives indicate that the ship was constructed in an area set between the North of Spain and the French region of Aquitania, probably in the Basque country. The construction of the ship was roughly dated to the year 1410 A.D., thanks to the 14C datings of the sealing moss used in the ship construction and the sediment below the shipwreck. The chronology obtained from several oak pieces of the ship, sampled and synchronized by Marta Dominguez of the Dutch Stichting RING Foundation, didn't fit to any dated master series from North and central Europe (Soberón et al 2012).

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The Foneria site

Location of the site and type of data

In 2009, due to a subway construction, an archaeological dig was carried on in Foneria street, in Barcelona, about four kilometers south-west from the city center. The site, that refers to a long rural occupation from the Iberian age to the Late Antiquity, is located in the deltaic area of the Llobregat river (Fig. 1), whose humid sediment allowed to preserve a great quantity of organic material. Particular attention was paid to a well, partially built in wood, and to the wooden and carpological material contained in its inner deposit[1].

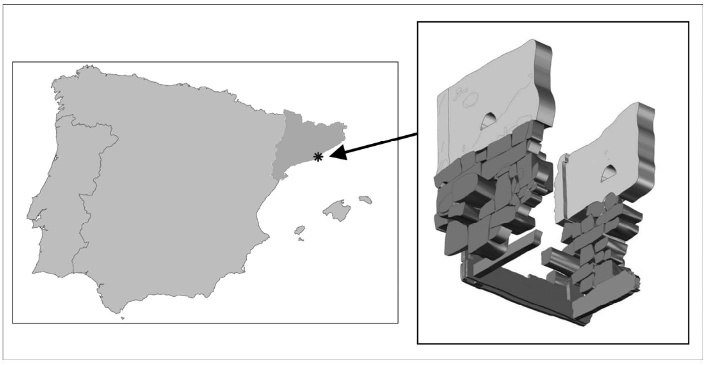

Figure 1: Location of the Catalan region and the Foneria site; 3D reconstruction of the well.

Those archaeological records relate to different historical moments: the well itself, that is being studied from the dendrochronological point of view, was built in the first phases of the Roman occupation of the site, and presumably its construction could be dated between the first and the second century AD; on the other hand, the stratigraphic unit contained in its interior was dated, by the presence of pottery sherds, to the sixth century AD, when the site was definitively abandoned. Both sets of evidences give us important information for the knowledge of the landscape and forest management in the Roman era: nevertheless, considering that the framework in which this contribution is presented is mainly focused on the tree-ring discipline and the fact that the carpological and other small wood remains will soon be object of a specific presentation in another context[2], here we will pay special attention to the well.

The well

The well, built mostly in masonry, with a squared shape, had an internal wooden lining in its lower extreme (Fig. 1), as per an already well-known technique, of which more examples are documented in Catalonia (Lopez Bultó 2010).

Almost all of the wood used in the well construction was identified as *Pinus sylvestris/nigra*, except one piece made of *Abies alba* (Lopez & Piqué 2010).

The wooden part was partially affected by the subway walls before the archaeological dig started, therefore it could not be entirely documented. However, it could be reconstructed as formed by four vertical elements, located at every angle of its square shape, and two opposite vertical sides

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[2] Several landscape aspects other than dendrochronological ones have been presented at the XVIII International Congress of Classical Archaeology, held in Merida (Spain) in May 2013, by A. Ravotto, R. Piqué and J. Ramos under the title of "Arqueologia espacial en el delta del Llobregat" and will be object of publication in the related proceedings.

formed by a series of planks that constitutes the internal lining of the well; on the other two sides, two big horizontal elements (a beam on one side, a thick plank on the other one) were used to keep the shape of the structure, while neither lining planks, nor hints of their presence could be found. Nails and a couple of types of joints (“mortise and tenon”, “half lap”) were used to assemble such structure. Several smaller pieces of wood were used to improve effectiveness of the joints between sets of planks that had different thickness.

This variety in thickness, as well as the diversity in the overall dimensions and shape among elements with similar structural function, and the presence in one of them of an unused hole for a joint, suggest that part of the wood was reused from a previous undetermined structure. While the morphological study of this one, in a hard attempt to achieve a hypothetical reconstruction, is still in course, it can be deduced at this stage that it was painted white. Residues of a patina of this color was documented in a couple of pieces, one of them being the one with the unused joint hole and both being part of the set of elements that could be crossdated.

Methodology

The wood from Foneria, like most of the examples of pre-modern times wood discovered in Catalonia during an archaeological dig, was preserved in a waterlogged state. Waterlogged wood characteristics and treatment are already described in general biography (Brunning & Watson 2010). It’s well known that while conserved in a saturated environment, it maintains its shape even if it is degraded by fungi and bacteria, since moisture fills the damaged structure. However, when water evaporates, its own surface tension causes cell collapse and shrinks the decayed wood (Brown 1991, Unger et al 2001). In the case of Foneria wood, and thanks to the availability of a great quantity of material that allowed to use a minor part of it for destructive analysis, a series of variables implied in the process of decay have been monitored. First, the water content of the wood has been calculated on small fragments of wood according to the “U max figure”, that can be used for a preliminary estimation of the state of preservation of the wood structure: depending on the piece considered, the result for the pines was between 247% and 620%, with an average value of 418%. This values denote a degraded wood, since in the case of pines such degrade is revealed by the presence of more than 250% of water content (Brunning & Watson 2010). The “U max figure” is, nevertheless, a very approximate indicator of the state of preservation of the wood. In order to relate it to an analytical evaluation of the decay, the cellulose still present in a sample with a content of water of 612% was determined in the Laboratory for radiocarbon dating of the University of Barcelona: it corresponded to the 8,2%, while the original content would have to be between 40% and 50% (Blanchette 2000).

At this stage, the main purpose of this investigation was not to identify the type of microbial attack that concerned the wood, but how the decay could affect a dendrochronological analysis and how this latter could be undertaken in the least expensive and most effective way. It has to be considered that the only way to integrate dendrochronology in ordinary “salvage archaeology” is limiting the costs of the entire process, a major part of which is represented by the chemical treatment necessary to the stabilization and preservation of wood.

While the wood was conserved in an appropriate tank filled with water, the effects of this decay have been monitored on a couple of fragments. In figure 2a it is shown the variation of dimensions of a sample of wood while naturally drying, at a temperature of 25ºC and 65% of humidity. Those variations were measured along four axis on the transverse plane of the stem: one along the radial direction and three along tangential directions, two of which corresponded to the directions given by the sides of the piece and determined by woodworking.

The diagram shows that the smallest shrinkage is produced along the radial direction, while the biggest is produced along the perpendicular to it. This decrease is partly due to the normal process of wood shrinkage when moisture evaporates, which also occurs on the fresh wood, but it is accentuated by the collapse of the cells of archaeological wood. Furthermore, due to the dispersion of the fungal action, shrinkage is not homogeneous and, even if series of ring measurements undertaken on damaged wood can often be synchronized, especially if they are carried out during the first 48 hours of drying, a stabilization treatment is required in order to assure the possibility of their repetition.

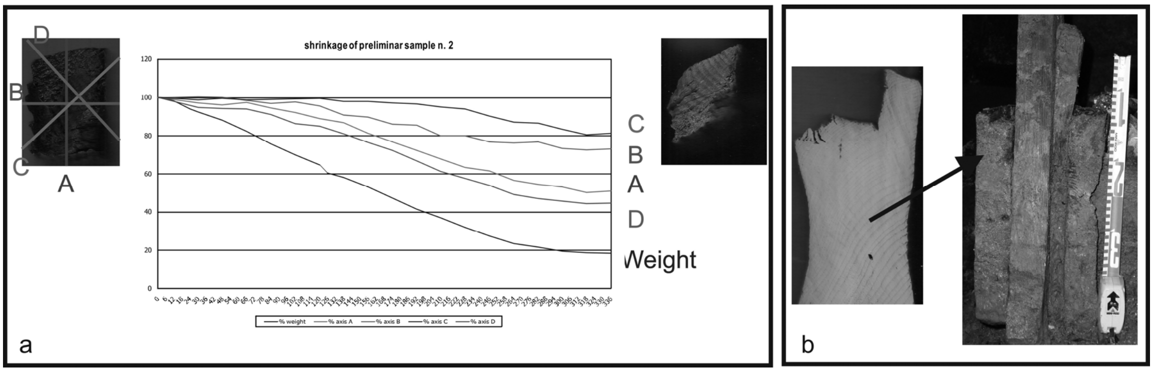

Figure 2: a) Percentages over time (in hours) of the shrinkage of a waterlogged wood fragment when dried naturally. b) A treated element that has maintained its "L" shape (left), as it results from the comparison with the same element in situ *(right).*

The standard stabilization and conservative treatment of wood, at present days, recourses to the freeze-drying and impregnation of PEG. If this technique seems to be almost essential in the case of large pieces of wood, it has the disadvantage of high cost and, from the dendrochronological point of view, it may make it difficult to read tree rings (Brunning & Watson 2010) and it makes 14C datings impossible (Unger et al 2001).

In the case of Foneria samples, the dewatering process was accomplished by a series of baths in hygroscopic solvents, since their lower surface tension with respect to water (dyn/cm 75,64) allows natural drying without destructive effects on the wood. Ethanol (dyn/cm 22,27) or acetone (dyn/cm 23,7) were used and no difference was noted in the final result.

Although bibliography usually considers this drying method as a part of consolidating treatments with rosins (Unger et al 2001), it has been noted that, in the case of small objects, such as dendrochonological sliced samples, the impregnation can be omitted, removing the risk of contamination that could affect subsequent analysis, like 14C dating.

The results were satisfactory. Not only shrinkage was reduced to minimal levels and rings remained clearly visible but also, as it can be seen in fig. 2b, it was possible to preserve the details of the piece even when its shape was somewhat complex, as is the case of the parts used in joints. However, even if during the four years following the treatment the treated samples didn't show any appreciable change, it has to be remarked that such treatment was not aiming to obtain pieces for long term conservation, as those that will be indefinitely stored in a museum. The purpose was actually to ensure the availability of samples for a reasonable period in order to undertake various analysis and even reproduce them for quality control.

Measurements of tree rings were taken on high resolution (4800 dpi) scanned images of slices of each piece of the well by CooRecorder software (Cybis Elektronik & Data AB). When it was possible, measurements along two opposite radii of the samples have been done. Cross dating operations were undertaken using the Cdendro software (Cybis Elektronik & Data AB) and later, after a visual confirmation of the matching of the curves, submitted to COFECHA quality control.

The chronology

Of the 13 pieces that composed the well, 8 clearly match (COFECHA series intercorr.: 0,62) to form a chronology of 130 years length (mean length of series: 73,3). Another one well matches to most of the types of correlation coefficient but it is too short (27 years long) and it's therefore not included in the chronology. One more piece might be aligned but, due a to a severe microbial degradation, the rings sequence is not entirely readable and is waiting to be re-measured on samples from other parts of the planks. The silver fir sample cannot be crossdated with any of the pine sample.

No sample retained the bark. Sapwood detection is somewhat problematic, because of the state of preservation of the waterlogged wood and the effect of the drying treatment, that tends to light the overall color. Anyway, the suspected sapwood has been confirmed by observing the penetration of an alcoholic safranin solution into the end grains of the samples (Bamber 1987). The sample with the most recent rings in the chronology (Fon02) probably retains the most part of the sapwood, which corresponds to a number of outer rings between 80 (judging by visual observation) and 90 (by considering the penetration of the stained solution), for a total thickness, respectively, of 6.5 and 7.5 cm.

Thanks to a preliminary 14C dating of the wood, the structure reused into the well construction can be dated roughly to the I century AD. Unfortunately, due to the lack of adequate references for conifers in the region, the chronology cannot be dated more precisely by correlation. For this reason, a series of ten 14C datings of two untreated and synchronized samples, on consecutive groups of five rings each, is being undertaken by the Laboratory of radiocarbon dating of the University of Barcelona in order to achieve a 14C "wiggle matching". The results will be appropriately divulged in the future.

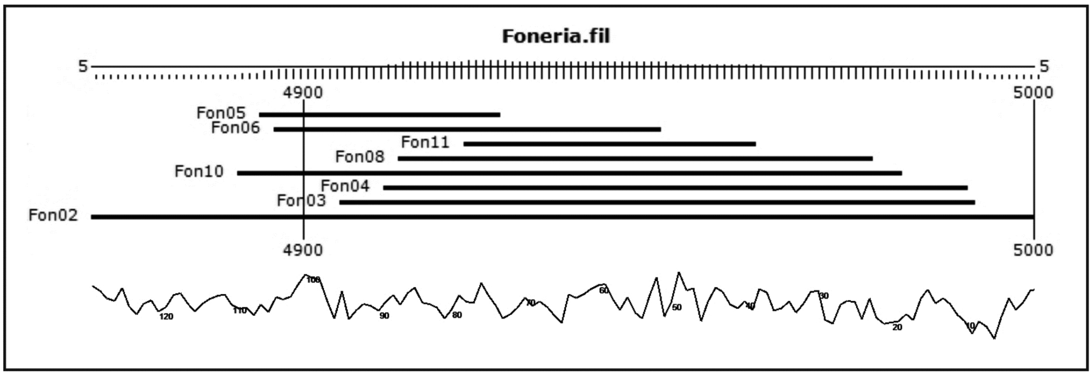

Figure 3: Chronology from Foneria. The tree ring curves of each series have been detrended by fitting a negative exponential curve, before the mean values chronology were plotted. Older times are on the left. The timelines of each series and the sample depth are in the upper part of the figure.

Some aspects of forest management during Roman times in Catalonia.

Before illustrating the punctual contribution of the Foneria data to the study of forest exploitation in Roman times, some words must be spent about the state of the knowledge on the subject in the Catalan territory. Research on this subject has been undertaken mostly thanks to carpological and pollen studies: since the publication of a couple of papers that summarize data scattered throughout the territory collected in the past (Buxò 2005, Riera 2005, where all the previous relevant bibliography appears), some new data can be deduced from more recent studies accomplished in mountain territory (Palet et al 2006, Riera et al 2011), where also studies on carbonized fragments of wood could be undertaken (Euba & Palet 2010), as well in the coastal zone (Palet et al 2010a; Palet et al 2012), where archaeobotanic records are integrated in a multidisciplinary archaeological approach.

Generally speaking, the present state of knowledge interprets human impact on woodland during Roman times mainly from the point of view of the relationship of the increase of farming, livestock and other productive activities with the decrease of forest surface, due to fires or tree felling. Although this association cannot lead to a homogeneous model applicable over the entire Catalan territory – deforestation is not a generalized process (Palet et al 2010) and landscape is characterized by several specific forms according to the chronology and the localization of the site studied, with special consideration to the difference between coast and mountain regions – we can assume that, in the Roman period, forest management had a greater importance compared to previous eras.

From the point of view of economic interests directly related to woodland or tree culture, for the time being the evidences allow to speak of several contexts for exploitation of trees.

In the first place, thanks to data scattered over the entire Catalan territory, the exploitation of tree for fruit production, either in the form of cultivated – autochthon or introduced - fruit trees (*Prunus avium, Ficus carica, Prunus persica, Prunus domestica, Prunus amygdalus, Corylus avellana, Juglans regia)* or in the form of recollection of wild products (*Prunus spinosa, Quercus sp, Sambucus nigra*) (Buxò 2005) is well known during all the Roman times.

Regarding the direct exploitation of tree wood, in north-east Pyrenees, between the I century BC and the II century AD, *Pinus sylvestris* and *uncinata* were used, probably in the form of charcoal, for combustion in metallurgic furnaces (Palet et al 2010b; Euba & Palet 2010) and, around the II-IV century AD, for the production of rosin (Palet et al 2010b; Orengo et al 2013). Recently, thanks to archaeobotanical analysis that allowed to reconstruct the environment of one of the major necropolis of Barcelona, researchers have pointed out the fact that, among local documented species (*Quercus ilex, Quercus robur, Olea, Pinus pinea* and *Pinus* spp., *Corylus avellana, Salix* spp*,* Cupressaceae), some had specific ritual values (particularly oak and pines) and could be used especially for the arrangement of funerary gardens (Beltran de Heredia et al 2007). Other activities that had to be very extended but are harder to document in archaeological contexts, since they cannot be proved by small charcoal or pollen record, such as manufacture of working tools (Euba & Palet 2010:179-180) or structural elements from *Pinus nigra*, *Abies alba* (Euba & Palet 2010: 180) and oak (Lopez Bultò 2010) are also known.

In the area around Foneria site, located at the bottom of the hill of Montjuïc promontory, on the edge of the deltaic plain of the Llobregat river, Roman landscape was reconstructed on the basis of pollen records as mainly forested, occupied by evergreen oaks, pine trees and deciduous trees, with several clearings for farming activity. It will only be from the Late Antiquity onward that deforestation acquires major proportions, thanks to the use of repeated wildfires in order to obtain more space for breeding, in correspondence to a decline of agricultural practice (Palet *et al* 2010a, Palet *et al* 2012).

Foneria archaeobotanical data add substantial information to the state of the knowledge of landscape management and plants distribution of this area, but, like we said before, carpological data and small plant remains are worth a specific presentation.

In this context, anyway, the Foneria well allows to set out an issue related to economic implications of the use of wood in the early Roman era. Mainly due to the limits of the set of data in previous studies of wood employment on the Catalan territory, researchers could not face the eventuality of wood supply from sources other than the local environment. Where the use of wood has been documented, it has always been related to the exploitation of woodland adjacent to the archaeological site. The sole, hypothetical, exception, negligible from the economic point of view, would be represented by handcrafted tools made of silver fir and boxwood that could have been transported by shepherds during transhumance for their personal use, dropped and burnt during summer stays, when unable to accomplish their function (Euba & Palet 2010:180).

The wood used in the well construction at Foneria, *Pinus sylvestris/nigra* and *Abies alba*, today cannot be found closer than, according to the species, 30 or 50 kilometers north and north-east in straight line from the archaeological site (see i.e. Moser et al 2013, fig. 4). Even if there is some evidence, like in other parts of southern Europe (Moser et al 2013), that silver fir was more widespread during the Roman period than it is today (Riera 2005), the pollen records of this era don't include it in places closer to the site than those of our time, since, like for European black pine and Scots pine, their natural environment is set from 500 m. above sea level upward.

This strongly suggests the hypothesis that those species, highly appreciated by Roman carpenters for structural woodworking (Ulrich 2007) were object of trade to Barcelona. They could arrive from the backcountry overland and, probably, given the proximity to the navigable Llobregat river (Izquierdo 2009), partly by fluvial transport, as it seems the case of silver fir transportation from the mountains of Etruria and Umbria to Rome through the Tiber River and its tributaries (Ulrich 2007). Nevertheless, for the time being, the possibility that structural wood could arrive by sea trade cannot be ignored: it's the way by which other types of construction material documented in the Foneria site were imported, like *tegulae* and water pipes. Even if it's not necessary to consider a more distant origin, sea routes could have been more practical for transporting wood from some northern coastal ports closer to the Pyrenees mountains.

Conclusions

The archaeological dig of Foneria site has provided useful information for landscape reconstruction in the coastal zone of central Catalonia. From the dendroarchaeological point of view, a well built in the early Roman empire times allowed to build the first chronology of Roman times on the territory and to deduce some assumption about wood transportation from inland. The find helped to raise awareness of dendroarchaeology with the relevant Catalan authorities for cultural heritage preservation, that funded subsequent analysis. Therefore it is hoped that, in the future, the potential of this discipline could be fully exploited thanks to the collaboration between the many qualified local dendrochronologists and the archaeological community, in order to improve the multidisciplinary approach to the everyday historical investigation.

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Archaeological woody plant remains as indicators of human selection and environmental changes

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Introduction

The importance of plants in the landscape of both the past and present is undisputable. This makes botanists' contributions essential as they are able to create a knowledge bridge that links past and present by providing a faithful interpretation of the plant cover in the territories occupied by past civilizations, and frequently also for settlements and human activities of today.

For this reason, biological archives preserved in anthropogenically disturbed layers are direct evidence of both the environmental evolution and cultural transformation. Plant remains from archaeological contexts can provide fundamental information on both past societies and environmental history. Archaeobotany is the study of plant remains from archaeological contexts, but in a modern sense and in a biological perspective it is more properly the study of plants from contexts disturbed by humans. Botanical remains constitute an important portion of our cultural heritage and an important palaeoenvironmental archive.

Plant remains have often been neglected and considered as additional and redundant in many archaeological researches. In the last years the sensitivity of archaeologists to natural issues is thankfully increasing and is opening new perspectives in the knowledge of our past (e.g. Masi et al. 2013a,b, 2014). The reconstruction of past environment in archaeological studies represents a fundamental issue and a challenge for bioarchaeologists (Mercuri et al. 2010, 2011; Sadori et al. 2014). Although archaeobotany is a fairly recent addition to the study of the past, it now makes use of many techniques, also from other disciplines, which are far behind classical archaeobotany. Here we present three different approaches to the study of arboreal plant remains, namely palynological, geochemical, and palaeogenetic analyses.

Palynology

Changes in vegetation recorded in pollen diagrams can provide essential clues to infer past climate such as abrupt decadal/centennial changes or long-term trends. The basic principle used in palynology is that trees are more water demanding than herbs, implying that forest opening attests less humid conditions, possibly occurring at times of temperature decrease/increase. This is true for time periods in which humans were not yet present, but the circumstances are more complicated in human-dominated times. Forest clearance can be in fact the effect of both climate change and human impact. Disentangling the two causes is a difficult and sometimes impossible task if independent, not human-induced, environmental data is absent (Roberts et al. 2011a, b, Sadori et al. 2011).

In the last two decades, research investigating climate change and human exploitation of the environment during the last millennia in circum-Mediterranean region has strongly increased. The importance of using palynology to assess past environmental features is well known as well as its application to archaeological reconstructions for studying the onset and evolution of cultural landscapes (Mercuri et al. 2011).

Lago di Vico is a crater lake located 50 km NW of Rome (central Italy, Fig. 1). Here we present a synthetic diagram of the top core of a long Pleistocene/Holocene record (Magri & Sadori 1999).

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Figure 1: Location map of Lago di Vico, Viterbo, Italy (basemap Esri).

The pollen diagram (Fig. 2) clearly indicates that important changes in the forest canopy occurred after 6000 years BP. The arboreal pollen percentages and concentration curves are respectively an indication of the physiognomy and of the health of a forest. Reading the AP (arboreal pollen) percentages we can understand the relations between woody and non-woody plants (NAP, non arboreal pollen are the complementary % up to 100, the whole).

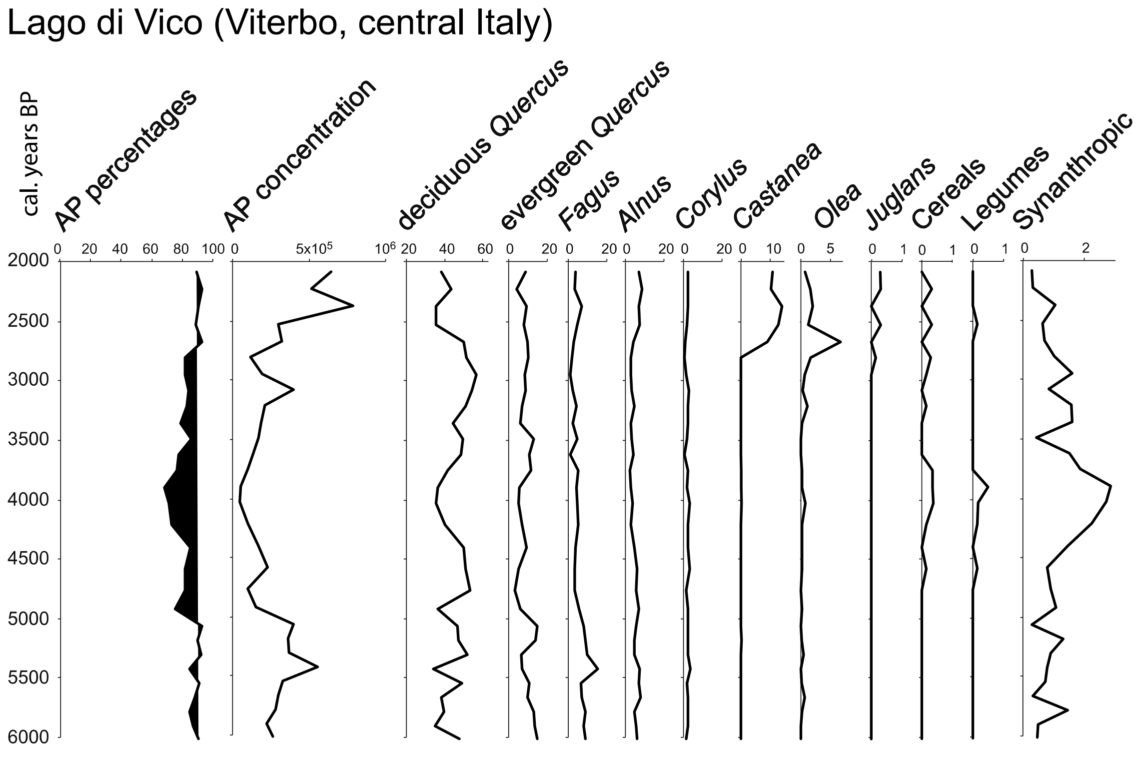

Figure 2: Lago di Vico. Simplified pollen diagram for the period between 6000 and 2000 years BP.

The pollen concentration is proportional to the pollen production and can be considered estimation of the biomass, of the vegetation thickness and lush. Forest clearance occurring at Lago di Vico at 5000 years BP (visible in the reduction of AP percentages and even more in AP concentrations) matches an increase of synanthropic taxa centered culminating soon after 4000 years BP, during the Bronze age. These increase of NAP is accompanied by slight and significant expansions of possibly cultivated herbs such as cereals and legumes. Cultivation of trees such as *Castanea* (chestnut), *Olea* (olive), and *Juglans* (walnut) is unquestionable since the beginning of the Iron age, around 2800 years BP.

The time window recorded in Figure 2 is a period characterized by important climatic changes all over the Mediterranean and at the same time by the blooming of Eneolithic, Bronze, and Iron age civilizations (Roberts et al. 2011a, Sadori et al. 2011). It is once more evident that palynology alone is not able to disentangle between environmental or human forcing in shaping the present-day landscape.

Geochemistry

The close relationship between humans and environmental changes in time and space is influenced by the use of plant products. The assessment of the role of human selection on the plant dataset, recovered from archaeological sites, is still one of the biggest problems in archaeobotany. Plant assemblages in archaeological contexts are always the result of human selection carried out in an environment shaped into a cultural landscape. An independent source of past climate reconstruction in archaeological contexts might come from the application of stable carbon isotopes analysis to archaeological charcoals to provide long climate and environmental records. In recent years, this approach has been extensively used to reconstruct past climatic and environmental conditions using fossil plants from archaeological sites (e.g. Aguilera et al. 2012, Baneschi et al. 2012, Ferrio et al. 2003, Masi et al. 2013a,b, Riehl 2009) all over the world and especially in the Near East.

A wide project for the study of charred archaeological remains from the site of Arslantepe (Malatya, Turkey, Fig. 3) is still running (Masi et al. in press). The site is located in the Malatya plain (eastern Anatolia) 15 km west of the Euphrates River. Arslantepe is a hill constituted by thick anthropogenic deposits that stratigraphically record the long and complex history of the site from the 5th millennium BC to the 8th cent. AD.

Figure 3: Location map of Arslantepe, Malatya, Turkey (basemap Esri).

The archaeological strata provided a huge amount of archaeobotanical charred remains (woods, seeds and fruits). In figure 4a charcoal data for five archaeological phases are summarized and grouped according to the ecological features of the taxa, pointing out changes in timber use during the five archaeological periods (from the Late Chalcolithic to the Early Bronze Age - from 3350 to 2000 years BC). The climate interpretation, as a rough qualitative estimate, is made with the water drops shown in Fig. 4b. The drops are intended as a reference to humidity, and their number and size are related to the wetness requirements for different trees. Changes in wood assemblages resulted useless to evaluate environmental changes (Masi et al. 2013a). The isotopic information can, on the contrary, be used to assess the influence of climate change on human cultures and to understand environment management (Masi et al. 2013b, in press). Charred wood remains of deciduous oaks and juniper have been analysed for the same archaeological period and for modern plants (Fig. 4c). It appears that the two curves show similar trends in the short period between ca. 2850 and 2500 yr BC, in which the curves are substantially parallel and the Δ^{13}C difference between them is quite reduced, but they are shifted by ca. 50 to 150 years in the rest of the record. For the interpretation of the arboreal curves, however, it was necessary to consider the autecology of modern plants and the source of the water used for photosynthesis, as the two selected trees show Δ^{13}C curves with rather different patterns. Overall, ^{13}C/^{12}C contrasting ratios in juniper and deciduous oaks suggest that seasonality in rainfall distribution and aquifer recharge played a complex role. Thus, a consistent seasonal contrast in precipitation (similar to the one in recent times) took place at ca. 3350, 3100 yr and 2300 yr BC indicating that semi-arid conditions have occurred in the past, in alternation with periods characterised by minor differences in the distribution of annual precipitation. Speleothems of Soreq cave in Israel (Fig. 4d, Bar-Matthews & Ayalon, 2011) suggest that a phase with high climate instability occurred between 3300 and 2900 BC, similarly to that recorded in the charcoals from Arslantepe.

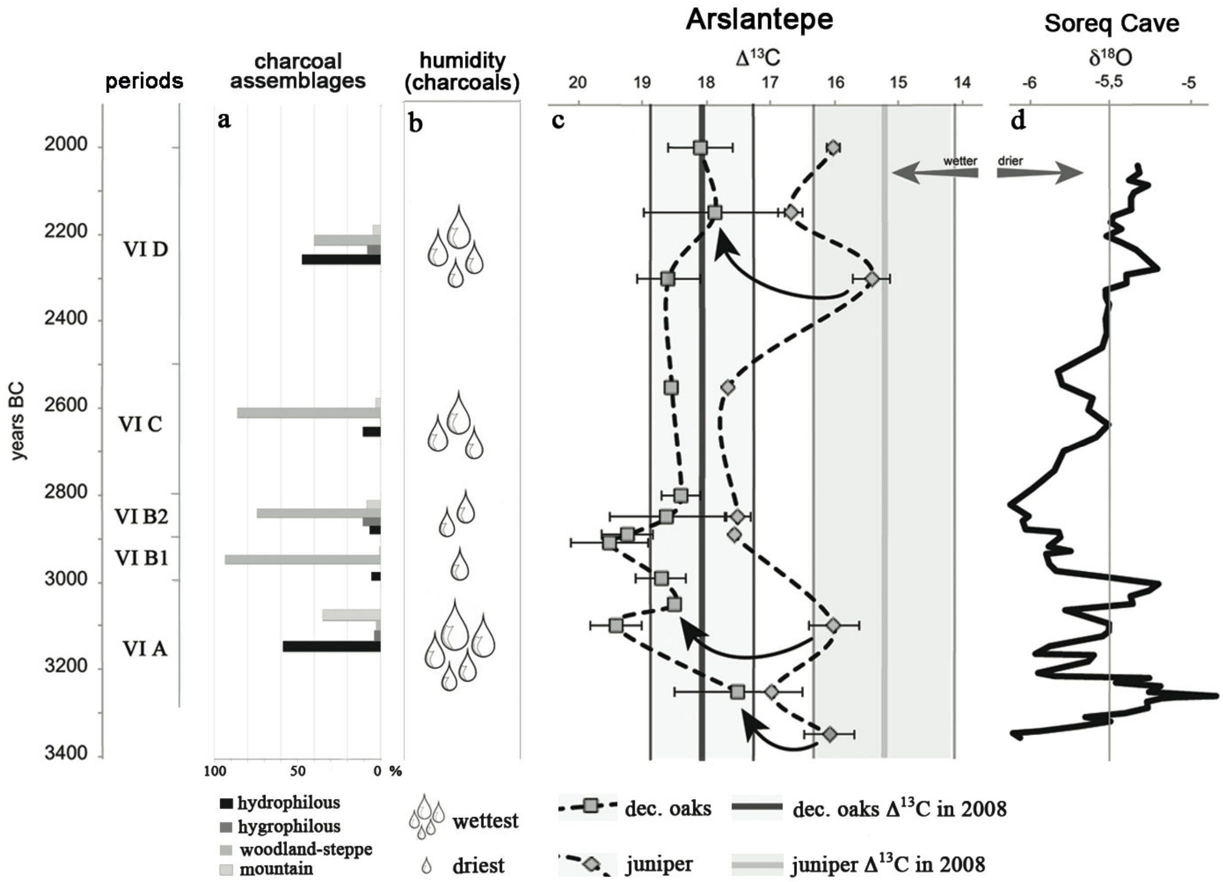

Figure 4: a: Percentage values of charcoal assemblages of the five archaeological periods according to ecological groups (hydrophilous taxa: Alnus *sp.,* Populus *sp.; hygrophilous taxa:* Fraxinus *sp.,* Ulmus *sp.; woodland steppe taxa: deciduous* Quercus*, Rosaceae; mountain taxa*: Pinus sylvestris ⁄ montana *group,* Juniperus *sp.). b: Estimate of humidity on the basis of the ecological features of charcoal assemblages. c: Δ^{13}C curves for Juniperus and deciduous Quercus. d: δ^{18}O curve of Soreq cave speleothem. a and b: Masi et al. 2013a, modified; c and d: Bar-Matthews & Ayalon 2011 and Masi et al. 2013b, modified.*

Genetics and palaeobotany

How long viable plant material is preserved is an important scientific challenge. Sediments from permanently frozen and temperate regions contain ancient evidence of higher plants, for which plant DNA sequences are known from 10 to 400 kya (Willerslev 2003), even if plant parts are not anymore visible. Also arid environments turned out to be suitable for preservation of biological material. Recently *Phoenix dactilyfera* (Sallon et al. 2008) and *Silene stenophylla* (Yashina et al. 2012) specimens were reproduced using plant tissues respectively 2 and 30 thousand years old.
As a matter of fact a massive boost was given to palaeogenetical studies on plants in the last 10 years and the number of articles present in the ISI database (Institute for Scientific Information, Web of Science) dealing with aDNA passed from 313, period 1985-2004 (Gugerli et al. 2005) to 552 for the period 2005-2013. For the period 1985-2004, the number of aDNA articles dealing with archaeological plant remains summed up to 13%, and most articles (43%) dealt with crops history (Fig. 5, Gugerli et al. 2005).

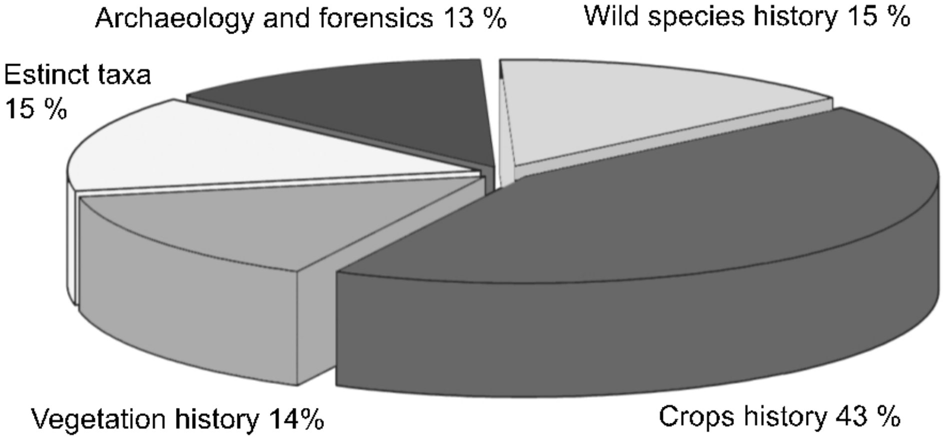

Figure 5: distribution of articles by subject included in the ISI database (period 1984-2005). Gugerli et al. 2005 modified.

In a EU project connecting palaeobotany and genetic aDNA (ancient DNA) extraction from fossil woods to test the genetic continuity between ancient and modern arboreal taxa taken from several archaeological sites. aDNA extraction was successful for 5 on 51 archaeological samples of deciduous oaks (Deguillox et al. 2006). In all cases, the haplotypes detected in ancient woods and the haplotypes characterised from fresh samples from the same localities matched. Overall, this congruence is consistent with a genetic continuity between ancient and modern European oaks, confirming the hypothesis that the mapped genetic patterns largely reflect the original structure that established during the post-glacial. This pattern is clearly visible along the coast of the Latium region (Fig. 6), where a good match between archaeological samples respectively from a palisade of Roman Imperial age (Fiumicino), and a shipwreck of Renaissance age found at the mouth of a river (Borgo Sabotino), and modern plants DNA (haplotypes) is found.

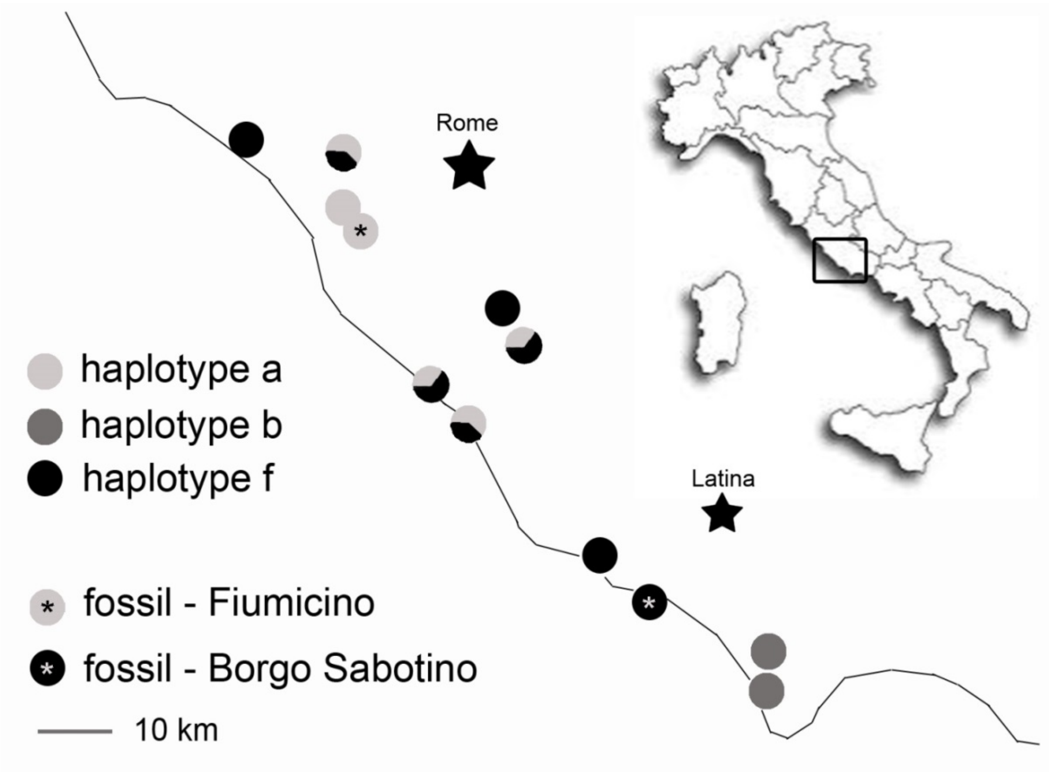

Figure 6: Haplotypes characterisation of oak populations surrounding the Fiumicino (Roma) and Borgo Sabotino (Latina) of woods remains of deciduous oaks. Deguilloux et al. 2006, modified.

In cases in which DNA was not preserved, present-day genetic data on living arboreal populations were compared with palaeobotanical data to assess the migration of past trees in order to locate glacial refugia (Cheddadi et al. 2006; Magri et al. 2006).

Concluding remarks

Recent advances in biological and geological sciences provide new tools in the study of plant macroremains from archaeological sites. The role of arboreal plants in the study of Cultural Heritage is essential to understand the relationships between climate, environment and human societies. It becomes more and more evident that multidisciplinary approaches bear valuable new information in archaeobotanical studies.

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SECTION 2

CLIMATOLOGY

Dendrochronological comparison of *Castanea sativa* Mill. and *Quercus pyrenaica*Willd. in southwest Spain

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Introduction

Chestnut (*Castanea sativa* Mill.) is a widely used species both for its fruit and wood harvests. The species has been introduced in Extremadura (SW Spain) in mid-mountain areas with almost 100 mm summer rainfall (Álvarez et al. 2000, Patón et al. 2006). This is the case in the “Sierra de Montánchez” (SM), an isolated mountainous area reaching 1000 m asl, where chestnut plantations have been established in the early 19th century replacing *Quercus pyrenaica* Willd. natural forests. Since then, it was common practice that both species, chestnut and oak, share certain ecological habitats (Álvarez et al. 2000), with chestnut being preferred due to its economic benefits in wood and fruit production.

SM is considered a special site with specific climate conditions allowing for forest coppice. Since the late 1960s, wood demand decreased due to the use of new materials. Accordingly, SM chestnut forest harvest terminated, and the administrative status of the forest changed towards a 'protected park'. With non-active forest management applied since then, a gradual decline of chestnut and subsequent invasion of other tree and shrub species occurred. The chestnut forests began to fragment and Pyrenean oak invaded into the habitat. This process of habitat regains and species replacement is widespread in the Mediterranean area after the termination of coppicing management (Fonti et al. 2006).

We here apply dendrochronological methods to study and compare tree ring width (TRW) variations in chestnut and oak in a shared habitat of SM over the past decades. We analyze the response of these species to different climate indexes to assess the sensitivity to changing environmental conditions in the Extremadura region, and to assess the dynamics of chestnut/oak competition.

Materialand methods

The Ecology unit of the University of Extremadura worked in different sampling campaigns in SM chestnut forest. In 2004, 6 *Castanea sativa* trees were sampled, obtaining 12 cores using increment borers. In the same way, 13 *Quercus pyrenaica* trees were drilled in 2011, obtaining 23 appropriate cores. In both sampling, the trees were selected from the bound of a chestnut coppice forest and inside including the young and old trees at 39 º 12 '58.85 "N and 6 º 08' 27.23" W, 800-825 m asl with a NW exposure. The samples were treated in the laboratory according to standard methodology (Speer 2010). A first visual crossdating was conducted using the Yamaguchi method, which consists of a classification of tree-rings according to their relative characteristics in diameter and/or special morphologies (Yamaguchi 1991) to establish an initial calendar.

The samples were then scanned at high resolution (2400 pixel ppp equal to approximately 0,011mm) with an Epson Expression A3 10000 XL scanner using the Debian Linux environment with the package Xsane (http://www.xsane.org). TRW was measured using the Image J software (http://rsbweb.nih.gov/ij/) with the plugin ObjectJ (http://simon.bio.uva.nl/objectj/index.html) specially developed for the measurement of TRW. A second crossdating was conducted using the measurement profiles determined by the BAR program of the DPL suite (Dendrochronological Program Library, http://www.ltrr.arizona.edu/pub/dpl/) considering 32-spline regression plots for visual comparison. This program helps to detect more detailed problems not previously detected by the Yamaguchi method. Once the samples were visually crossdated, we analyzed the TRW data using the COFECHA program (Holmes, 1983).

To remove age trend and associated variance we used ARSTAN software (Cook 1985). We opted for a negative exponential curve for detrending and calculated ratios from negative exponential functions fitted to each individual TRW measurement series (Cook and Peters 1997,Düthornet al. 2013). We used the same settings for both species (Tab. 1) and considered the residual chronologies for further analyses (Fig. 1; Fig. 2).

Table 1: Chestnut and oak chronology characteristics.

Species	Samples	Period	Cofecha inter-series correlation	Mean TRW (mm)	Standard deviation	Lag-1 autocorrelation
C. sativa	12	1943-2003	0.582	3.40	1.926	0.677
Q. pyrenaica	23	1946-2010	0.540	0.25	0.139	0.650

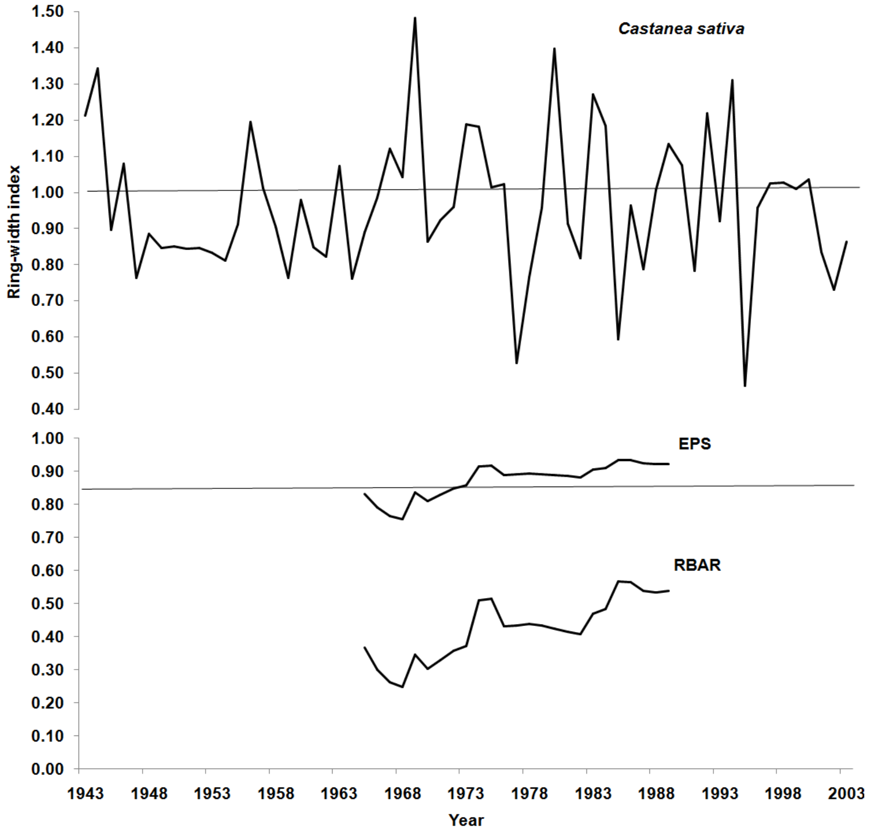

Figure 1: Castanea sativa residual chronology, and EPS and RBAR values.

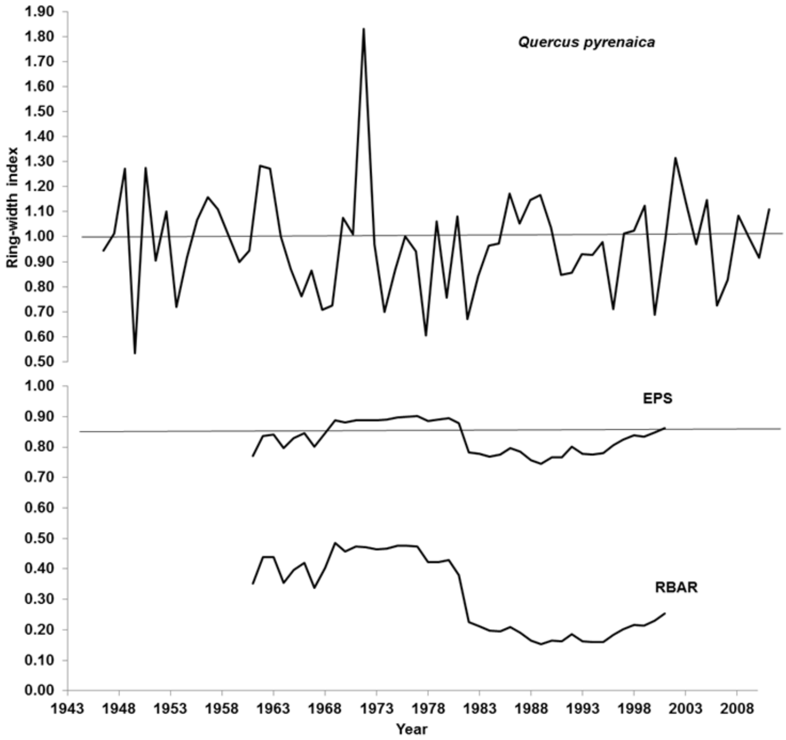

Figure 2: Quercus pyrenaicaresidual chronology, and EPS and RBAR values.

Due to SM is specific climatic conditions in contrast with the surrounding area (400 m altitude difference), selecting representative climate data had to be careful. The principal idea was to choose instrumental data from locations close to the sampling site to ensure unbiased analyses between TRW and monthly climate data. To assess and mitigate potential biases, we finally considered four different data sources (Fig. 3): (a) the Montánchez climate station with only monthly rainfall records, in 2 km distance from the sampling site and no significant altitudinal difference; (b) temperature and rainfall data from the Alcuéscar climate station, in 8.5 km distance and altitudinal difference of 280 m; (c) North Atlantic oscillation (NAO) station derived data (including the Lisbon observatory); and (d) gridded temperature, precipitation and Palmer Drought Severity Index (PDSI) data from KNMI (http://climexp.knmi.nl).

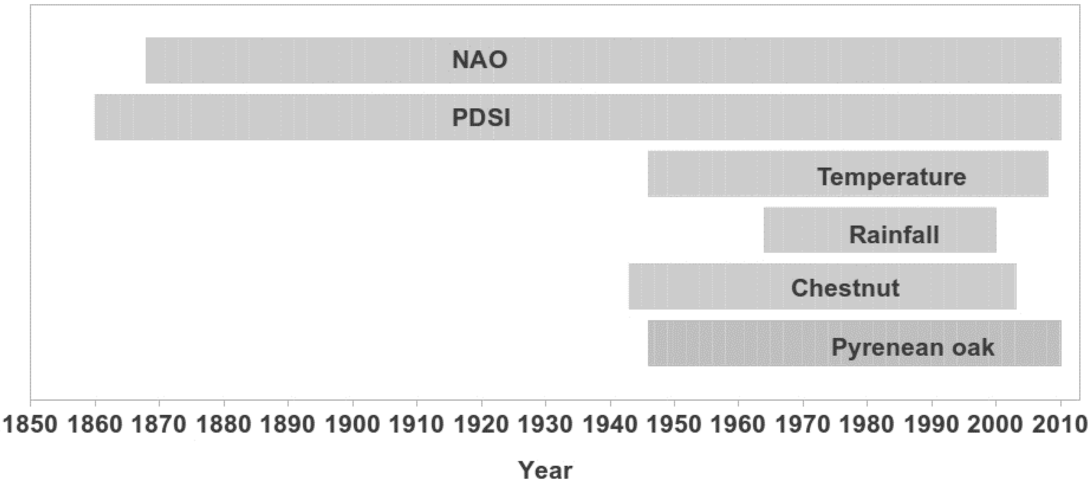

Figure 3: Periods covered by the instrumental temperature, rainfall, PDSI, and tree-ring data used in this study.

Pearson correlations were calculated to assess the association between TRW chronologies and (a) rainfall, (b) temperature, (c) PDSI, and (d) NAO data on a monthly, seasonal and annual basis. In order to account for potential memory effects previous year measurements were considered additionally. In addition to these calibration trials based on continuous time series, we extracted pointer years from both chronologies using a two standard deviation threshold, and analyzed the climatic parameters during these extreme years.

Results and discussion

As previous studies of this species in the region showed (Roig et al. 2009), chestnut can be correlated with the NAO index (Tab. 2). On the one hand, both species share a similar correlation to the spring rainfall, as an indicator of similar ecological niche. On the other hand, the negative correlations of the pyrenean oak with maximum April-August temperature could be explained because in southern Spain it is a species related to mountains, with an altitudinal gradient. Since SM is located close to its lower altitude distribution limit, high temperatures during April-August could restrict its growth (Pérez-Ramos & Marañón 2009). Chestnut, as a Mediterranean species, is better adapted to these temperatures if water availability is sufficient during the growth season, specifically in summer (JJA) period (Roiget al. 2009, Patón et al. 2006).

Table 2: Significant ($p < 0.01$) correlations between the chestnut and oak chronologies and climate variables over the 1946-2003 period.

Chronology	Mar-May rainfall	Apr-Aug max. temperature	Jun-Aug PDSI	Dec NAO
C. sativa	0.42			0.39
Q. pyrenaica	0.42	-0.40	-0.40	

In table 3 the results of the pointer years analysis are displayed. *Castanea sativa* showed strongly reduced growth in the climatically interesting years 1977 and 1995. 1977 was not a dry year in its annual mean rainfall, but for an important part of the growth season, namely the spring period (MAM), it was the driest throughout all recorded years with only 55 mm of accumulated rainfall (mean is 195 mm, see Tab. 4).

Table 3: Positive (+) and negative (-) pointer years exceeding +/- 2 standard deviations.

Pointer Years	*C. sativa*	*Q.pyrenaica*
1949		-
1969	+	
1971		+
1977	-	
1995	-	

Table 4: Castanea sativa pointer years and relationship with climate.

	Mar-May rainfall [mm]	Mar-May minimum temperature [ºC]
1977	55	-0.17
Climate average	195	2.95
	Annual rainfall [mm]	Mar-Aug maximum temperature [ºC]
1995	560	35.2
Climate average	770	32.8

At the same time 1977 is also the coldest year of the entire climate record of minimum mean spring temperatures. In this sense, we must notice that the temperature data is from Alcuéscar station with an altitude difference of 250 meters to the sample point, so in SM it could have been even colder. 1995 is one of the driest years of the 20th century in Spain, within a big drought period that started in 1991 (Llamas, 1997). Chestnut responds to a combination of the lack of rainfall - only 560 mm annual rainfall (770 mm is the annual mean) - and the highest spring+sumer (MAMJJA) maximum mean temperatures (Tab. 3). The residual chronology of *Quercus pyrenaica* is rather complacent in the years 1977 and 1995. However, this chronology marks positively in 1971, when the climatic data reveal the highest summer (JJA) precipitation and the highest summer positive values of PDSI. The years 1949 (*Quercus pyrenaica*) and 1969 (*Castanea sativa*) are not accompanied by significant climatic events (Tab. 3). We assume non-climatic effects dominated growth in those years.

Conclusions and outlook

In the wake of the correlations with climatic factors of both residual chronologies and the analysis of pointer years, it is not possible to explain the dynamics of Sierra de Montánchez chestnut forest by taking only a single climate parameter into account.

However, the analysis of pointer years indicates that the chestnut is more sensitive to various combinations of different climatic indicators such as low rainfall and extreme (cold and high) temperatures. In this sense, *Quercus pyrenaica*, as a mountain oak at this latitude, is perfectly adapted to the environment with different ecological strategies as higher root biomass accumulation (Ruiz-Peinado et al. 2012), better adapted leaves for drought and evapotranspiration than chestnut leaves, even marcescent leaves that protect the branches of herbivores (Svendsen & Claus 2001).

For future research it will be necessary to use multivariate data analysis to determine the exact weight of different factors that affect to the chestnut TRW. It is also necessary to apply techniques from forestry and ecology in combination with dendrochronology to better understand the dynamics of Sierra de Montánchez chestnut forest.

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Stability of natural and modified timberline at Babia Gora Mt., Carpathians

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Introduction

The timberline ecotone is a very sensitive environment, which is susceptible to all changes occurring within. For the last century the most significant factors influencing the dynamics of its biotic elements have been anthropopression and contemporary climate changes (see review by Körner 1998). The migration of alpine plant and animals species to higher altitudes can be observed all over the world, however the scale and intensity of this process varies depending on the examined region (Peterson 1994, Parmes 1996, Pauli et al. 1996, Hughes 2000, Walther 2000, Kullman 2001). Whereas the upper timberline in the Tatra Mountains migrated by 200 m a.s.l. within the same area, as much as 30% of its length have not changed location for the last 60 years (Guzik 2009). The purpose of the research was to: i) determine the character of timberline at Babia Gora massif in the years 1964-2009, ii) identify the areas of stable timberline, iii) specify the elements responsible for its stability.

Study area

The study on timberline stability was conducted in the northern part of the Carpathian Arc, in the Beskidy Group, in the massif of Babia Gora (1725 m a.s.l.) (Fig. 1). It is a single isolated massif (80 km^2) with well-developed climatic-vegetation zones and alpine timberline, consisting of Norway spruce (*Picea abies*), located at the mean altitude of 1380 m a.s.l. The massif is distinguished by asymmetrical shape, with a steep northern slope and a gentle southern slope. Owing to greater yearly exposure to sunlight, timberline on the southern slope runs 70 m higher than on the northern slope. The difference between the highest and lowest location of timberline is 400 m a.s.l. (from 1106 to 1509 m a.s.l.).

Four stable parts of timberline ecotone were singled out for detailed dendrochronological analyses. The first two selected sites included forest growing on steep slope (inclination of 35^0) with northern exposure (NGS and NSS), while the next two sites were of south-east exposure on more gentle slope (up to 30^0) – the latter ones were affected by human activity in the past (SNS, SRS).

Materials and methods

Cartographic and photogrammetric analysis

Photogrammetric analyses of aerial photographs were used in the study – the oldest ones available for the area dating back to 1964 and the most modern ones from 2009. Timberline was analysed and classified according to changes, which took place from 1964: progressive timberline (timberline increased the height a.s.l.), regressive (timberline decreased the height a.s.l.) and stable (changes not exceeding more than 10 m).

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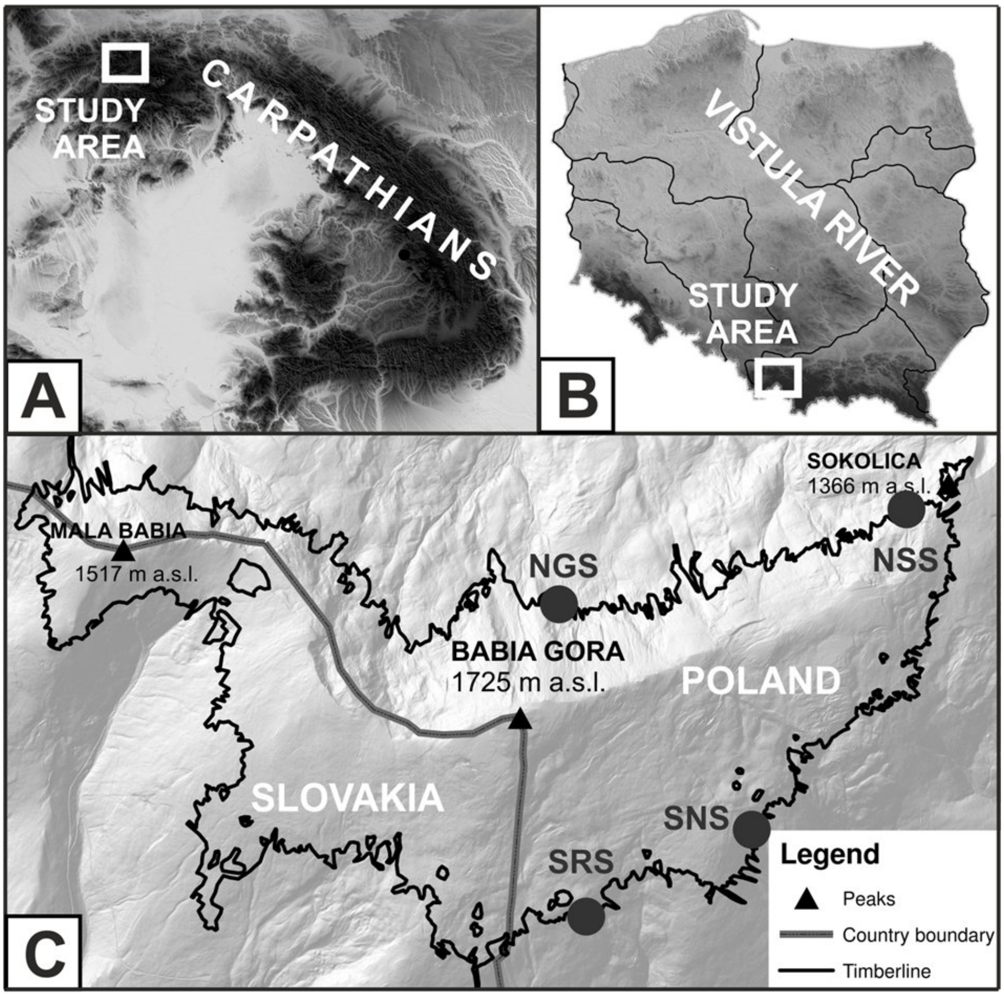

Figure 1: Study site localization in the Carpathian Mountains (a) and in Poland (b). Dendrochronological study sites localization of stable parts of timberline at Babia Gora Mt. (c).

Dendrochronological analysis

Four sites at the stable upper timberline were selected on the basis of photogrammetric analyses, where spruce stands were thoroughly examined by breast-height sampling of at least 60 trees (dead or alive) with Pressler's drill. Samples were dissected according to standard techniques applied in dendrochronology and tree-ring widths were measured (employing Cdendro software of Cybis Elektronik & Data AB company). Cofecha program (Holmes 1983, Grissino-Mayer 2001) was used to check the correctness of the measurements and time series consistency. Residual chronologies were built using Arstan (Cook 1985) software. Cubic smoothing splines with a 50% frequency-response cut-off at 200 years were employed and their variance was stabilized over time. Expressed Population Signal Index and Rbar were calculated. It was examined in which years and with what intensity missing rings occurred, indicating stressful environmental conditions. Breast-height age was assessed for all sample trees, by estimating the number of missing rings towards the tree pith with the Duncan method (1989). The trees were divided into ten year-age classes, the average age was calculated and the age structure of the stand was examined (even-aged stands or stands with complex age structure). Dendroclimatic analyses were carried out by employing mean monthly temperature (1949-2004) and monthly precipitation data (1948-2003) from the meteorological database CRU.310 (Haris et al. 2014) .

Results

Contemporary timberline at Babia Gora is 37 km long and shortened by 7% (2.6 km) during the investigated 45-year period. Its average elevation increased by 24 m a.s.l. and at present it is at 1380 m a.s.l. The average timberline altitude on the northern slope was stable over 45 years (1330 m a.s.l.) whereas on the southern slope it increased by 35 m a.s.l. (from 1365 to 1400 m a.s.l.). 61% of the timberline ecotone in the analysed period did not indicate any changes in location. Especially on the northern slope, where upper zone stands are semi-natural, 79% of the timberline revealed stability (Fig.2).

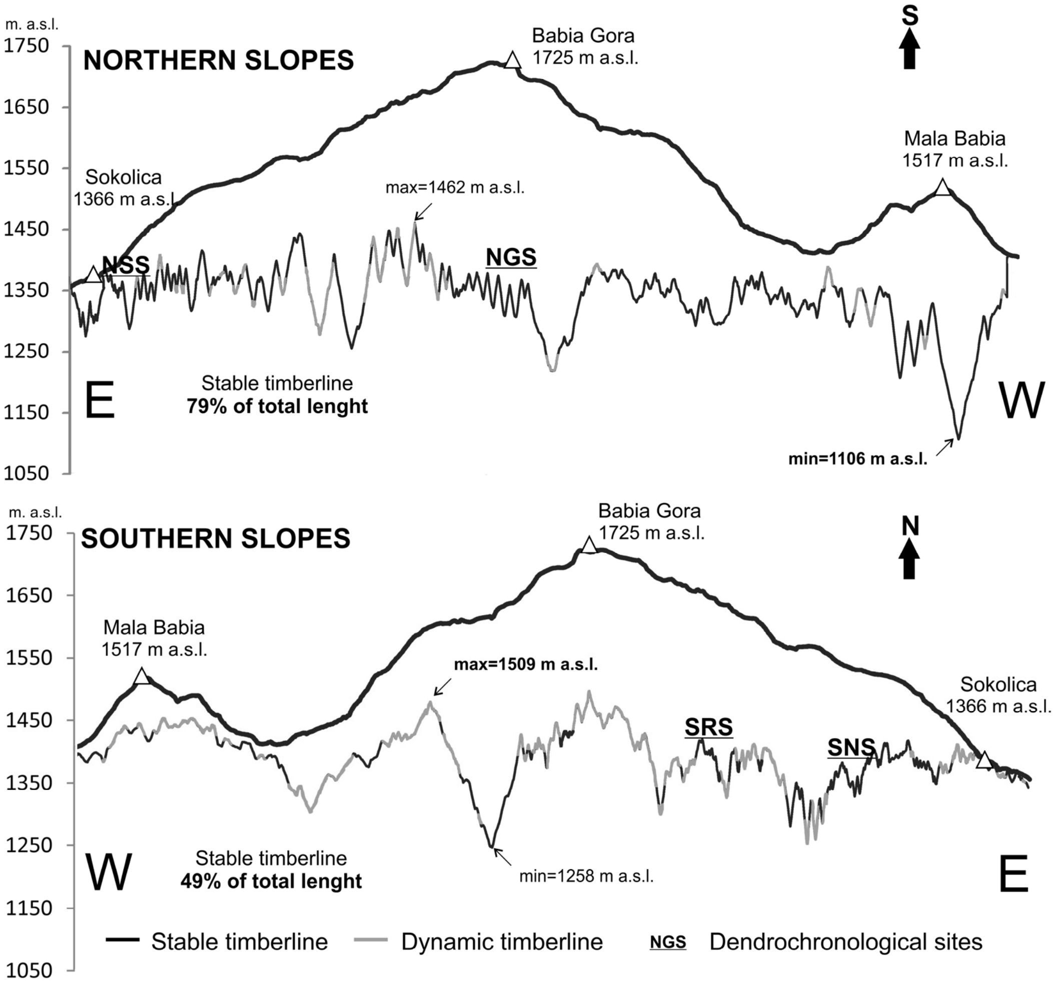

Figure 2: The current (2009) course and character of the timberline on the northern and the southern slope of Babia Gora.

The developed chronologies extend over 120 (SNS) to 250 years (NGS). Missing rings appear rarely, except for the period from the end of 1970s to the mid-1980s, when they were found in 22% of spruce growing at the NSS site and in 12% of trees at the NGS site. Such a situation was not observed for trees growing on the southern slope (Fig.3).

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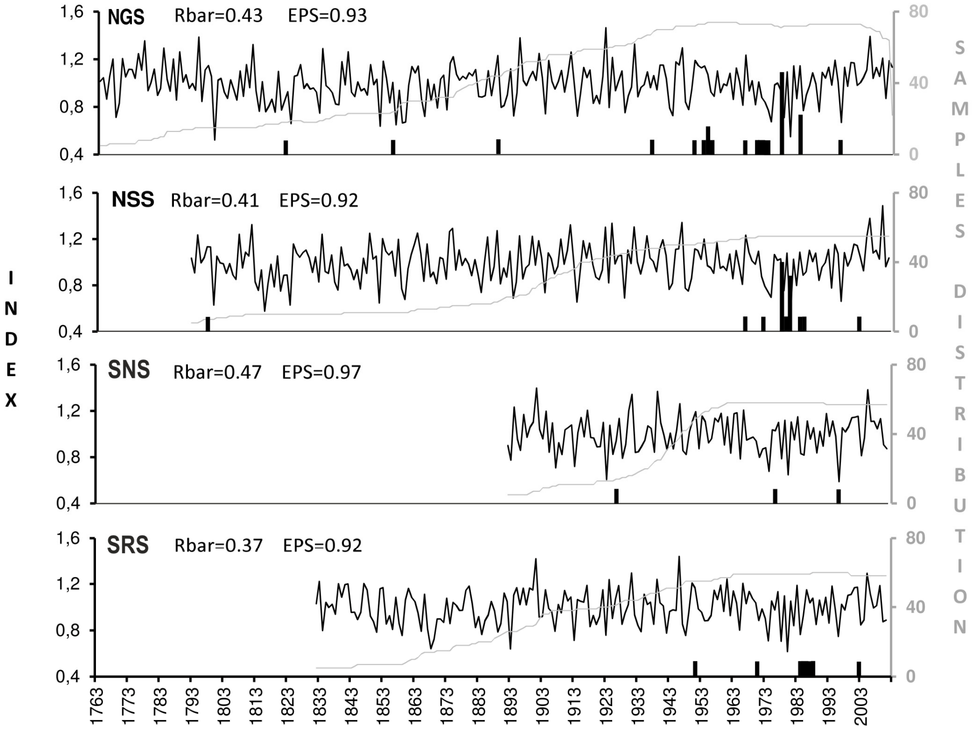

Figure 3: Residual chronologies (black curve) with sample distribution (grey curve) of four study sites at stable timberline at Babia Gora with Rbar and EPS. Black bars show the number of missing rings.

Analysing the age structure of the examined spruce stands we can distinguish two stand types. (1) Spruce at the NGS, NSS and SRS sites is characterised by complex age structure, and moreover, in case of the first two sites there is a long history dating back to the beginning of 18th century. It is also proved by a high standard deviation of the trees age (SD > 40 years). (2) The SNS site stands out against the rest owing to its even-aged tree generation, where 76% of trees spread from 1920s to 1940s (Fig. 4).

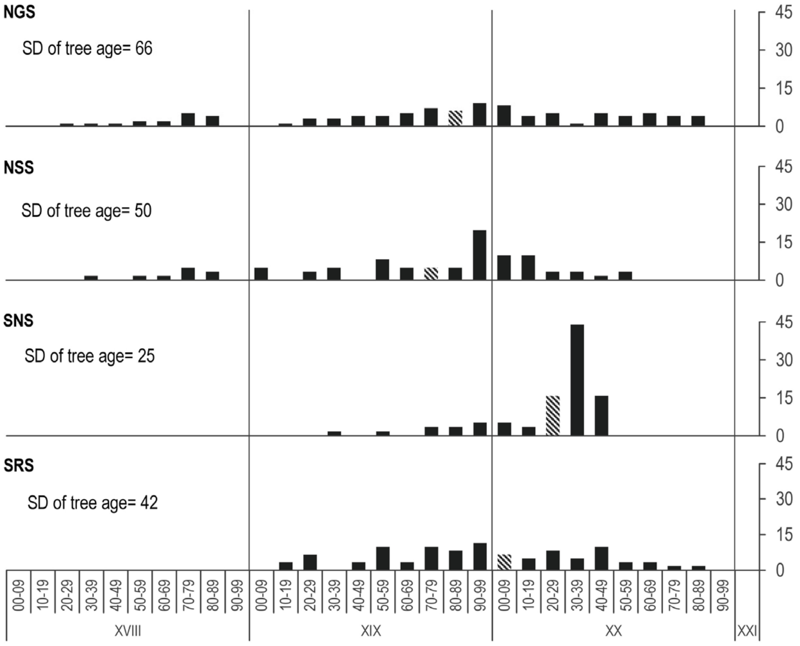

Figure 4: Trees age structure at four study sites grouped in 10-year classes. Striped columns show mean age of the stand.

The stand at the SNS site is the youngest and it developed as a result of liberation from environmental pressure, whereas the timberline ecotone at the NGS site is a semi-natural upper zone coniferous forest, located on a convex landform between two avalanche paths (Fig. 5). 80 years ago at the present location of the SNS site timberline ecotone there were singular groups of spruce, which did not make up a forest. Nowadays there is a sharp and clear boundary between the upper zone coniferous forest and dwarf mountain pine belt were trees reach up 2 m high. The growth of spruce at the NGS site is limited and, at the same time, stabilised by extreme geomorphological phenomena – snow avalanches. The oldest trees are in the central part, virtually in one line, giving protection for younger generations. Vegetative reproduction of spruce through roots and branch footing, which is a phenomenon characteristic of extreme ecological environment, was observed here (Kobendza 1922 after Vorčák, Jankovič 2009).

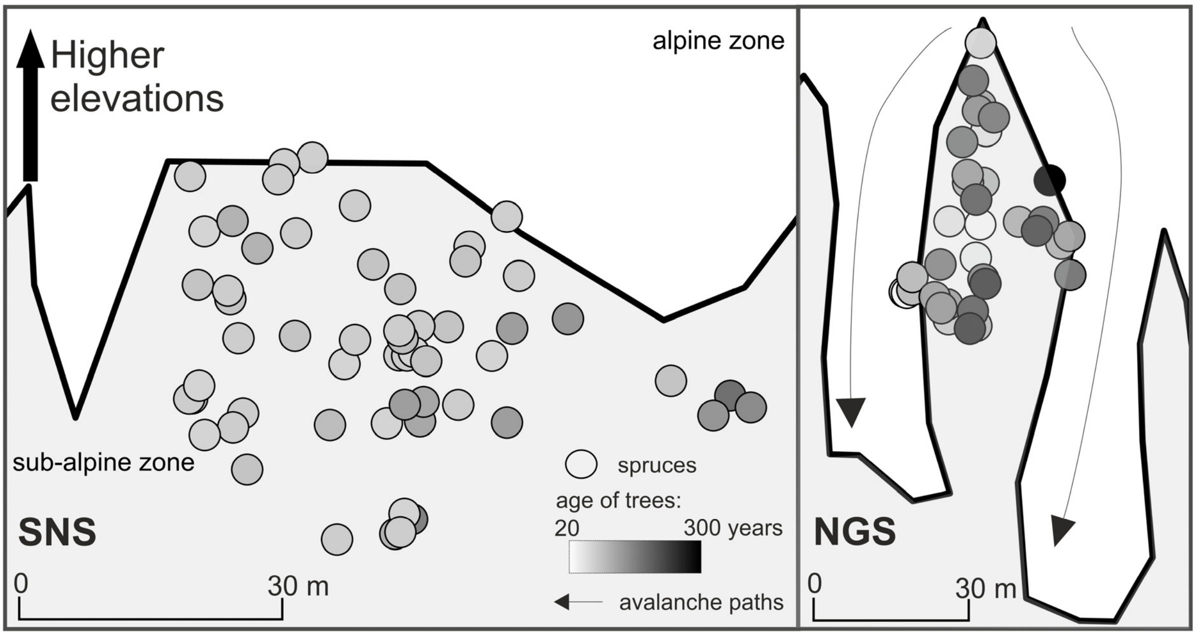

Figure 5: Spatial distribution of trees at SNS and NGS site.

Dendroclimatic analyses indicated that spruce ring width is highly dependent on climatic conditions – temperature and precipitation. Trees growing on the northern slope (NGS, NSS) and at the SNS site (the southern slope) indicate a strong connection with summer temperature (June – July), with correlation coefficients within the range 0.63-0.54. Whereas for the SRS site the most important factor is the positive influence of temperatures of the entire vegetation period: April - September (correlation coefficient: 0.58) (Fig. 6).

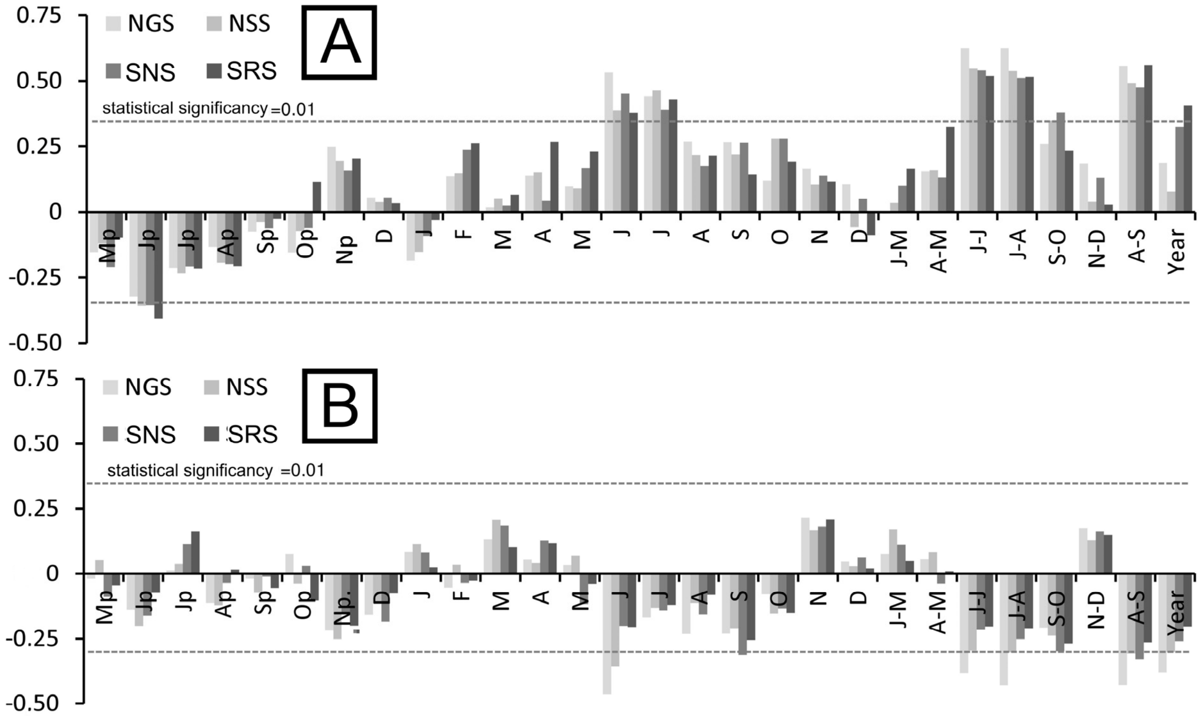

Figure 6: Response to mean monthly temperature (A) and precipitation (B) of trees growing on the four sites of stable timberline at Babia Gora Mt.

Precipitation in vegetation period (the average amount for April – September in this region: 690 mm) indicate a negative impact on the growth of these trees, however this factor is not as important as temperature. Only trees growing on the northern slope (NGS and NSS) are sensitive to this climatic element (correlation coefficient: -0.465 and -0.357 respectively).

Conclusions

In this part of Europe, beside Babia Gora, timberline appears in four other mountain ranges: Karkonosze (Śnieżka 1602 m a.s.l.), Tatras (Gerlach 2655 m a.s.l.), Bieszczady (Tarnica 1346 m a.s.l.) and Pilsko (1557 m a.s.l.). The stability of the timberline at Babia Gora in comparison with a similar, in terms of habitat, timberline type in the Tatras and Karkonosze is unique. In the Tatra Mountains the timberline dynamics is considerable – as much as 60% of its length changed even by 200 m in comparison to 1950s (Guzik 2008). Also in the Czech Karkonosze significant changes in the course of the timberline, related to both natural and artificial factors, were observed (Treml 2007). Only in the Bieszczady virtually no changes concerning timberline were noticed, however its ecotone is made up of beech and fir, which are more resistant to environmental changes but less flexible than spruce (Kucharzyk 2006). It is thought that the semi-natural character of the upper zone coniferous forest on the northern slopes of Babia Gora is the main reason of timberline stability there (Balon 2007).

It was observed that spruce stands of a complex age structure with several generations and history of sites dating back to 18th century appeared at three out of four sites. It proves that timberline environment at these locations was either undisturbed or just slightly modified. The timberline site SNS reveals stability in the analysed 45-year period, however the development of the ecotone at this location was closely connected with the liberation of the environment from human pressure in 1920s, when protection forests developed according to the principles regarding reserves (Szafer 1963). It is reflected by an even-aged stand at this site.

Semi-natural timberline stands of complex-age structure at the NGS site developed, as an ecosystem, their own strategy of survival in extreme climatic conditions, additionally modified by snow avalanches. An example of this strategy can be new trees growing in places protected by older trees or common autovegetative reproduction (Vorčák, Jankovič 2009). These mechanisms are not visible in the human-transformed ecotone (SNS), which is at the reconstruction stage.

Irrespective of the history of timberline stands development, climate is the most important factor limiting and stabilizing the growth of trees in the upper zone coniferous forest at Babia Gora. The results implying the greatest influence of vegetation period temperature are consistent with the existing research into timberline. Mean temperatures of vegetation period within the range 5.5-7.5^{0}C (regardless local climatic conditions) are directly connected with the location of timberline (see review by Körner 1998).The timberline at Babia Gora shows the same sensitivity to temperature as *Picea abies* growing on other ranges of the Western and Eastern Carpathians (Kaczka 2007).

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The signature of natural and anthropogenic climate drivers in treerings from the south of the Iberian Peninsula

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Introduction

Past temperature variations are usually inferred from proxy data or estimated using global climate models (GCMs). Comparisons between climate estimations derived from proxy records and from GCMs offer the possibility to identify deficiencies in both approaches and help to better understand mechanisms driving climate variations.

Based on tree rings, natural external forcing such as solar irradiance variations and volcanic activity have been highlighted as the main global driving mechanisms of natural climate variability on multidecadal to centennial time-scales during the Holocene (Briffa et al. 1998, Crowley 2000). However, the amplitude of the reconstructed variations in Total Solar Irradiance (TSI) and the possible limitations of tree rings to record the full magnitude of volcanic cooling are now being debated (Krivova & Solanki 2008, Mann et al. 2012). The lack of knowledge is even larger regarding the role played by anthropogenic forcing on climate, with Land Cover Changes (LCC) being an especially intriguing target since they may play an opposed role on climate when considering different spatial scales (Pongratz et al. 2010). The increasing availability of long climate-sensitive tree-ring chronologies and derived climate reconstructions, especially in underrepresented areas, will assist in developing a more accurate temporal and regional characterization of the natural and anthropogenic climate drivers.

July to October temperature variations reconstructed for the last 800 years based on tree rings from the Cazorla Range (NCZ_{Tjaso}) are compared to single-forced simulations driven by volcanic forcing (VF), LCC, solar forcing (SF), and concentration of greenhouse gases (GG) performed with the climate model MPI-EMS (Jungclaus et al. 2010). Additionally, the reconstruction is also compared to two ensembles of simulations (E1 and E2) with complete external forcing but different SF performed with the same GCM. The main aim is to identify the main drivers of the summer temperature variations at the southeast of the Iberian Peninsula.

Material and Methods

Reconstructed temperatures

July to October temperatures variations are estimated in the Southeast of the Iberian Peninsula for the last 800 years based on tree rings and climate model simulations. The reconstruction is derived from a tree-ring width chronology (TRW) composed of 40 *Pinus nigra* subsp. *salzmannii* (Dunal) Franco individuals growing at the Cazorla Range with tree ages between 250 and 900 years. Based on the relationships between ring width and climate, July to October temperature was identified as the main driver of tree growth (Dorado Liñán et al. 2011). Calibration/verification tests were carried out in two split periods. The linear regressed subsets of the TRW indicated a stable

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relationship between proxies and climate and preservation of high-to-low frequency variability (for more details see Dorado Liñán et al. 2013).

Simulated temperatures

The global GCM simulations used here were produced with the MPI-ESM model, which is an atmosphere-ocean model including a fully interactive carbon cycle (for more details the reader is referred to Jungclaus et al. 2010). The present study made use of the MPI-ESM simulations performed with just one external forcing at a time and two existing five-member and three-member ensembles of model simulations with full external forcing named E1 and E2 respectively. The ensemble of simulations E1 and E2 include identical volcanic (Crowley et al. 2008), LCC (Pongrazt et al. 2008), orbital (based on Bretagnon & Francou 1988) and aerosol forcing (Lefohn et al. 1999, Boucher & Pham 2002). The difference between both ensembles of simulations lies in the solar forcing applied: E1 uses a TSI curve of smaller amplitude of variations (Krivova & Solanki 2008) while E2 was driven by a TSI reconstruction with wider amplitude of solar variations (Lean 2000).

The most widely used volcanic activity reconstructions (Crowley et al. 2000;Gao et al. 2008) were also compared to the NCZ_{Tjaso} extreme years to assess the effects of volcanic eruptions at annual scales. The extreme years where defined as years with a temperature value exceeding the double standard deviation from the mean.

Results and Discussion

NCZ_{Tjaso} describes 800 years of summer-to-autumn temperature variations in the south of the IP covering the transition from the Medieval Climate Anomaly to the Little Ice Age (MCA-LIA transition), the LIA, and the modern times (Fig 1a).

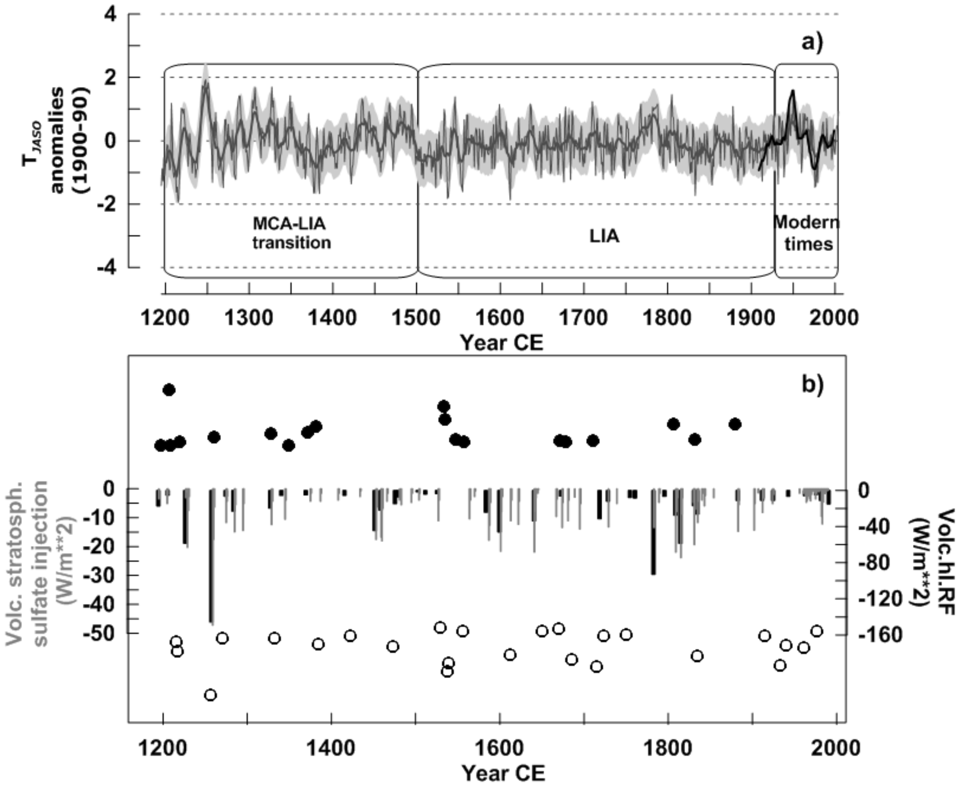

Figure 1. NCZ_{Tjaso} and volcanoes. a) Annual and 10-yr smoothed NCZ_{Tjaso} (thin and tick grey lines respectively) and the annual confidence intervals (grey shade). Superimposed is the 10-yr smoothed instrumental record (black line); b) comparison of positive (close circles) and negative (open circles) temperature extremes in NCZ_{Tjaso} and volcanic activity reconstructions from Crowley (2000) (grey line) and Gao et al. (2008) (black line).MCA: Medieval Climate Anomaly; LIA: Little Ice Age.

The MCA-LIA transition, defined here as the period 1200-1500CE, was predominately warm, with some alternating periods of low temperatures. The LIA is well marked and the cold period spans 1500-1930CE with only one positive anomaly between 1760-1800CE. The end of the LIA was followed by an increase in temperatures between 1925-1975CE, reaching a maximum in the middle of the 20th century. The most recent decades (1975-2003CE) have not been the warmest of the record.

When analyzing extreme years at NCZ_{Tjaso}, the negative events match in timing and magnitude to some known periods of explosive volcanic eruptions (e.g., 13th century) (Fig 1b). However, some periods of high volcanic activity do not seem to have impact on tree growth and summer temperature (e.g., 18th and 19th centuries). Likewise, some periods of high frequency of negative temperature anomalies do not seem to be linked to volcanic activity (e.g., 20th century).

At decadal to multidecadal scales (Fig 2), the correlation between NCZ_{Tjaso} and the single-forcing simulations as a function of increasing smoothing of the series (Fig. 2) reveals volcanism as the only external forcing with a significant correlation with decadal variations of summer temperature at the Cazorla Range during the last 5 centuries (Fig. 2b). Furthermore, the influence of volcanism is detected throughout the 19th and 20th century, though the correlation coefficient is at the limit of the 95% significance level (Fig. 2c).

We could not find a sustained significant correlation with SF nor with the other single-forcing simulation in the periods 1500-2000 and 1860-2000CE. LCC seems to attain a more prominent role in constraining summer temperature variations at the IP during the last two centuries, while the 20th century increase in anthropogenic greenhouse gas concentrations does not seem to have a discernible influence on the temperature trends at the Cazorla Range (Fig. 2c).

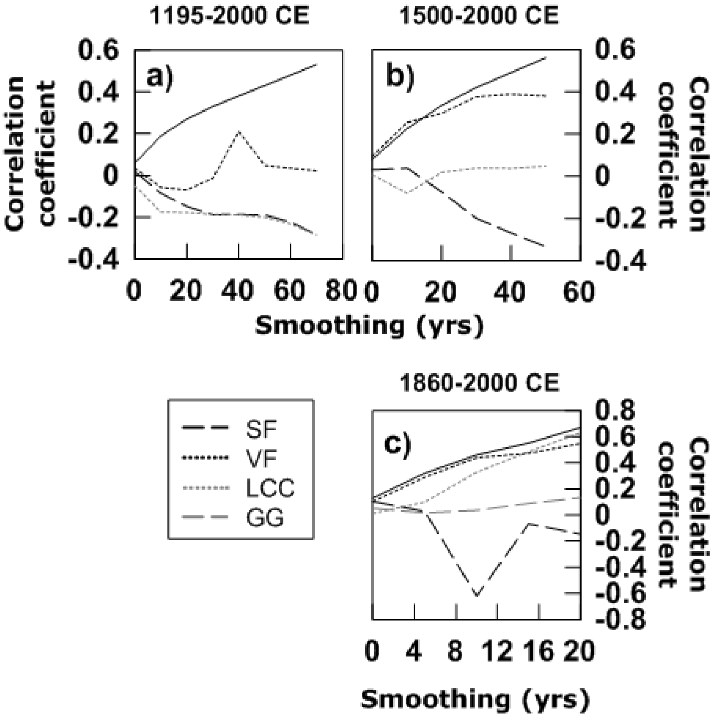

Figure 2. External forcing at Cazorla Range. a, b) correlation between NCZ_{Tjaso} and the simulations LCC, SF and VF as a function of increasing smoothing of the series for the periods 1195-2000 and 1500-2000CE, respectively; c) evolution of the correlation with increasing smoothing between NCZ_{Tjaso} and all simulations for the period 1860-2000CE. Black line indicates 95% significance level.

The correlation analysis of NCZ_{Tjaso} with the single-forcing MPI-ESM simulations used here provides some insights into the influence exerted by each forcing over the long period considered. However, this approach cannot fully explain more short-term or punctual influences.

Indeed, NCZ_{Tjaso} do better agree in amplitude and variability with the ensemble of simulations with a complete external forcing (E1 and E2) indicating that temperatures variations are not driven by a single forcing and they are most likely the result of a combination of several external factors. Among the simulations with a complete external forcing, NCZ_{Tjaso} reveals a closer agreement in terms of amplitude with the temperature variations simulated by the ensemble E2, forced with a TSI curve of wider amplitude of solar variations.

The amplitude of past solar variations is one of the key questions still under debate and the results found when comparing simulated and reconstructed past temperature are often contradictory. For instance, while our results indicate that models forced with TSI curves of wider amplitude lead to temperature amplitudes closer to those reconstructed, other authors found exactly the opposite (e.g., Hind & Moberg 2012).

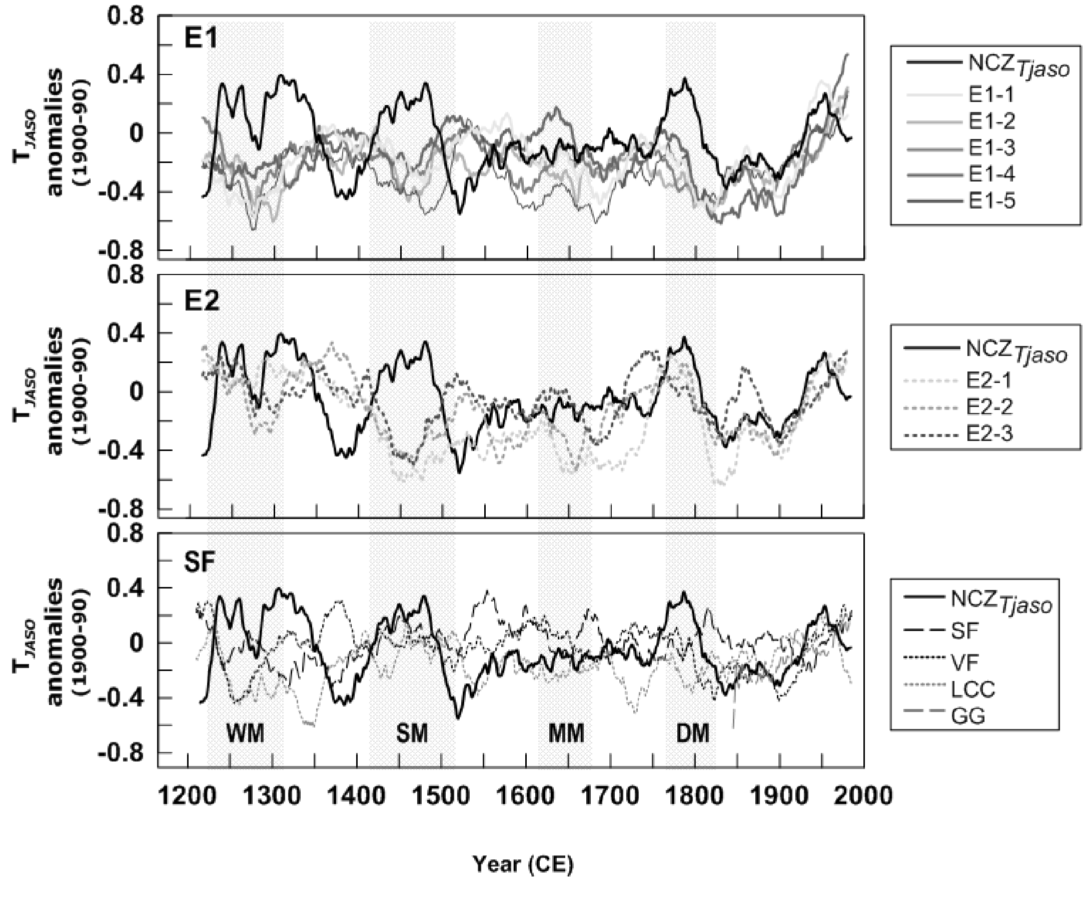

Figure 3. Comparison of reconstructed summer temperatures at Cazorla Range (NCZ_{Tjaso}) and those simulated by the MPI-ESM: ensembles E1, E2 and the single-forcing simulations (SF) in top, middle and bottom panel respectively. Periods of solar minima are shaded: WM (Wolf minimum); SM (Spörer Minimum); MM (Maunder Minimum) and DM (Dalton Minimum).

NCZ_{Tjaso} does not show significant correlations with any of the forcings when considering the whole period reconstructed 1200-2000CE (Fig. 2a). This is probably due to the fact that reconstructed and simulated temperatures are strongly anticorrelated during the MCA-LIA transitional period (Fig. 3). The comparison of the two ensembles of model simulations (E1 and E2), the single-forcing simulations and NCZ_{Tjaso} reveals a persistent anticorrelation spanning approximately the period 1200-1400CE. Previous studies also reported such anticorrelation across simulations performed with different GCM and proxy-based reconstructions (i.e., González-Rouco et al. 2011). Some authors pointed to a period dominated by internal variability, and therefore not forced by any of the tested forcing factors, as a reason for such differences (Mann et al. 2009, Graham et al. 2011, Trouet et al. 2012).

Conclusions

Volcanism shows up as the main factor controlling tree growth in our study area for the last 5 centuries at annual, decadal to multi-decadal time-scales. However, VF alone cannot explain the full range of summer temperatures variations in Cazorla Range. The role played by SF and anthropogenic forcing such as LCC during the last millennium could not be clarified and GG do not seem to be the dominant influence in the 20th century temperature variations.

The temperature amplitude shown by NCZ_{Tjaso} agrees better with that displayed by models including TSI reconstructions of wider amplitude. However, the anti-correlation between the reconstructed and simulated temperatures during the MCA-LIA transitional period highlights the current limitations in the attribution of such a temperature pattern to internal variability or external forcing.

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Heterogeneous climate signal in *Pinus sylvestris* tree-ring chronologies from southern Finland

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Introduction

Northern Europe is often considered to be a hotspot for proxy-based climate reconstructions, especially when considering tree-ring chronologies (Eronen et al. 2002; Helama & Lindholm 2003; Büntgen et al. 2005; Büntgen et al. 2008; Nicolussi et al. 2009; Esper et al. 2012). Typically, the growth pattern found in tree-ring width (TRW) chronologies from high latitude areas, such as northern Scandinavia, correlate well with summer temperatures (Helama et al. 2009; Grudd 2008; Gouirand et al. 2008). The climate signal changes with decreasing latitudes, from the arctic area to more moderate climate regions, from growing-season temperature towards precipitation, drought and non-climatic factors such as stand dynamics (Lindholm et al. 2000). A drought signal has been found in chronologies from southern Finland (Lindholm et al. 2000; Helama & Lindholm 2003; Helama et al. 2005; Helama et al. 2009) and Sweden (Drobyshev et al. 2011). These studies all point to the importance of tree-ring chronologies from lower latitude sites in Scandinavia to reconstruct long-term drought and precipitation variability.

In general, spatial analyses are necessary to increase the validity of climate signals in tree-rings (Gouirand et al. 2008; Treydte et al. 2007). Tree ring climate signals are affected by the age of the trees (Carrer & Urbinati 2004; Esper et al. 2008; Linan et al. 2012) as well as the sampling strategy (Tegel et al. 2010). Also more statistical processes, as RCS detrending, could influence the chronologies and therefore the correlation coefficients between the time-series and the climate target (Briffa & Melvin 2011). Düthorn et al. (2013) showed that trees growing in differing micro-sites produce different regional curves and contain differing climate signals.

Here, we assess the homogeneity of the climate signal and the signal strength across a network of 28 *Pinus sylvestris* tree-ring chronologies in southern Finland (60-65°N/23-33°E) and examine the influence of chronology characteristics such as mean replication, mean age, growth rate and latitude on the retained climate signal.

Tree-ring proxy and climate target data

The location of the 28 tree-ring sites herein examined is shown in Figure 1. Twenty-four chronologies were downloaded from the ITRDB and expanded by four recently sampled sites, considering ecological differences as moist soil conditions directly at lakeshores and drier soil conditions a few meters away from the lakeshore (Düthorn et al. 2013). The chronologies differ in length (119 to 395 years), replication (21 to 134 series) and were sampled in different years (1978 to 2011). Biological age trends were removed using 67% splines (as in Lindholm et al. (2000), Helama and Lindholm (2003)). This means that the rigidity of the spline is 2/3 of the length of every single time-series with a 50% frequency cut-off (Cook & Peters 1997). For calibration , we used monthly precipitation data from the GPCC V6 2.5°grid (Schneider et al. 2011) over the 1902-1978 period common to all tree-ring chronologies. The average of four grid points was considered and might best represent the widely distributed station data from Punkaharju, Lappeenranta, Helsinki, Tampere, Jyväskylä, Kajaani, Turku and St. Petersburg used in previous studies.

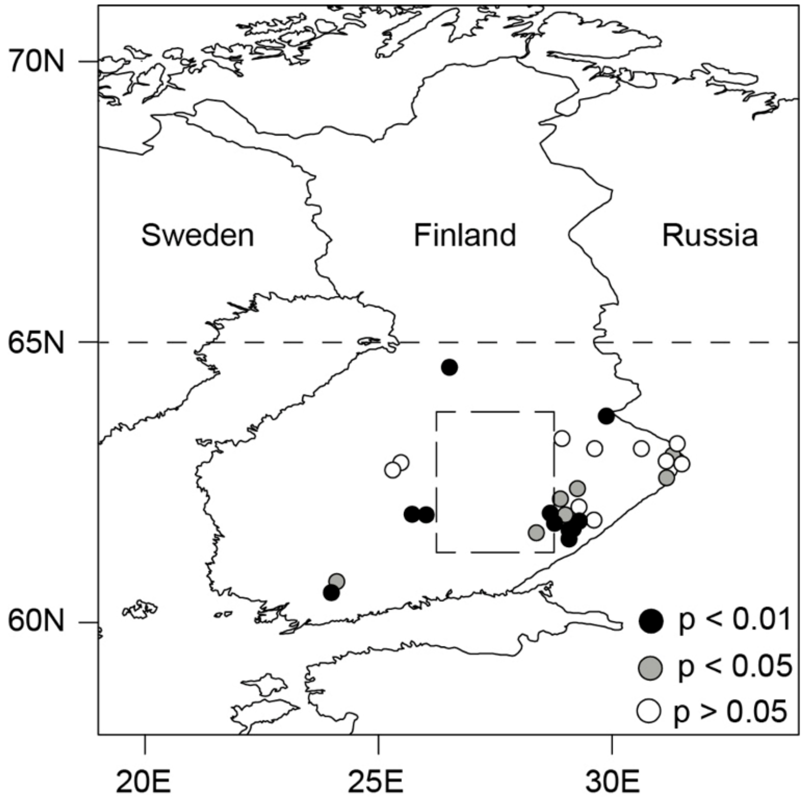

Figure 1: Location and climate signal strength of the 28 Pinus sylvestris tree-ring sites located south of 65°N in southern Finland. The colours (black, grey, white) indicate differing significance levels of the correlation of tree-ring chronologies with the sum of previous year May and June (pMJ) and current year May and June (MJ) precipitation calculated over the 1902-1978 common period.

Results

Growth pattern

The correlation matrix in figure 2 shows the inter-site correlations among all 28 TRW chronologies. Correlation coefficients range from -0.24 to 0.88 indicating no homogeneous growth pattern throughout the region. The matrix does not contain spatial patterns, i.e. neighboring chronologies do not necessarily correlate better than distant chronologies. The matrix also highlights the chronologies deviating from the general pattern, e.g. F24 showing low and negative correlation values with all other tree-ring sites. Other chronologies, e.g. F13 and F15, indicate rather high inter-site correlation. The mean correlation of all sites is 0.36.

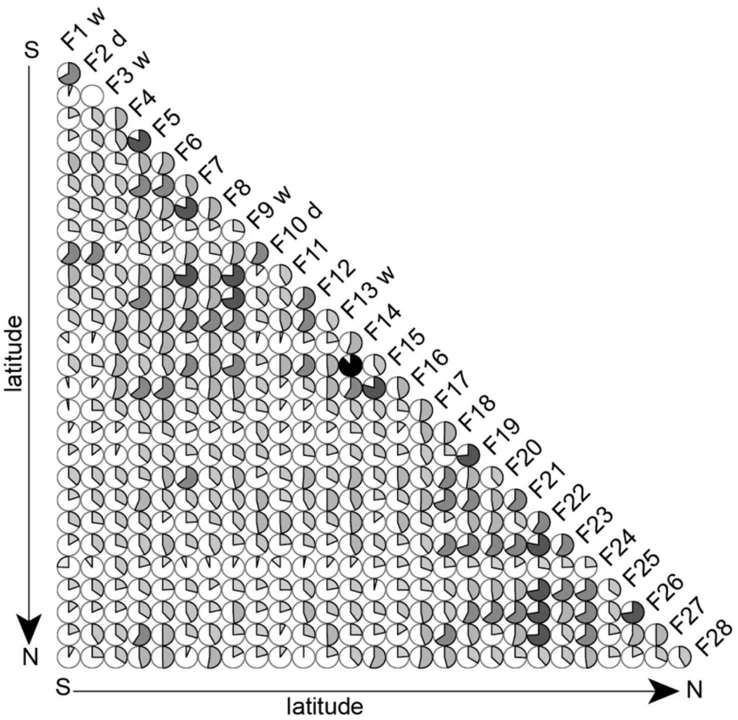

Figure 2: Correlation matrix of 28 tree-ring sites (F1-F28) ordered in south-north direction. Pies filled in clockwise direction indicate positive correlation. Pies filled counter clockwise indicate negative correlation. The darker the colour of the pie the stronger the correlation is. The extensions "w" and "d" indicate chronologies sampled at a lakeshore and drier inland micro-sites, respectively.

Growth-climate response patterns

The relatively moderate climate in southern Finland is expected to decrease the strength of the climate signal, because the limiting factor is likely to be less strong as compared to semi-arid or very cold areas (Linderholm et al. 2010; Speer 2010). In order to determine growth-climate relationships of the 28 sites, correlations between monthly precipitation and the single tree-ring chronologies were calculated (Fig.3a). Highest correlation values were found with previous year May-June (pMJ) and current year May-June (MJ) precipitation. In general, the climate signal is not uniform throughout the study area (Fig.3b). Eighteen of the 28 tree-ring sites (black and grey bars) show significant (p <0.05) correlations with early summer precipitation, and most significant responses were found with pMJ and MJ precipitation. The sum of these two seasons (pMJMJ) is thus considered in further analysis in order to assess the strongest common climate signal.

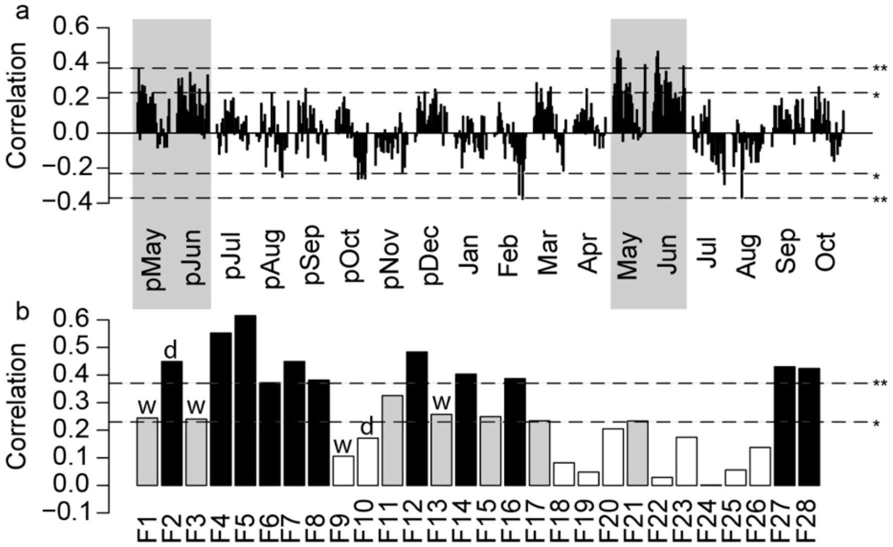

Figure 3: (a) Correlation coefficients of every tree-ring site (F1-F28) with monthly precipitation data of previous year May to current year October over the 1902-1978 common period. (b) Correlation results with pMJMJ precipitation sums over 1902-1978. Colour denotes the statistical significance reaching from p<0.01 (black) to p<0.05 (grey), and p>0.05 (white). Dotted lines indicate estimates of the 99% (**) and 95% (*) confidence level. Sites are ordered from lower (F1) to higher (F28) latitudes.

Differences in growth patterns between the sites are reflected in the high variability in significance of correlations. Figure 4 shows the 11 chronologies with the highest correlation (*p*<0.01) with pMJMJ (top) and the 10 chronologies with the lowest correlation (*p*>0.05) with pMJMJ (bottom). The correlation between the mean of these chronologies with pMJMJ reach $r_{p<0.01}$=0.63 in figure 4a and $r_{p>0.05}$=0.16 in 4b.

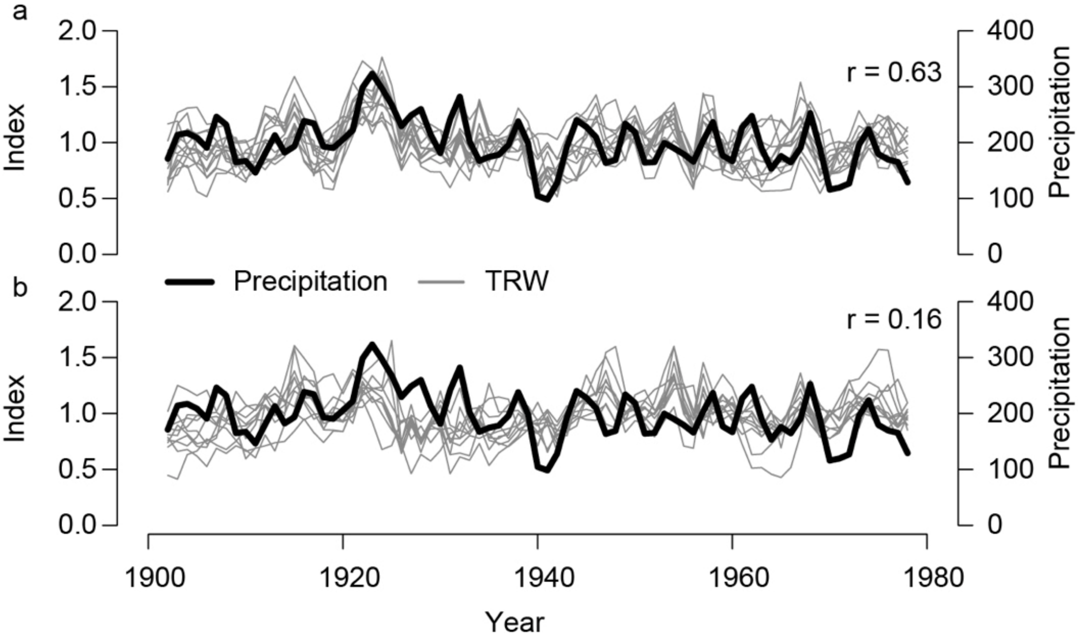

Figure 4: Site chronologies (grey) and pMJMJ precipitation (black) for the chronologies reaching (a) highest significance (p<0.01) and (b) lowest significance (p>0.05). Correlation coefficients derived from the mean of the site chronologies in the top and bottom panels with pMJMJ precipitation over the 1902-1978 period.

Correlation analysis

Due to different contributors of TRW data in the International Tree Ring Data Bank (ITRDB) and our own sampling strategy, the complete dataset is rather heterogeneous in terms of site-specific replication, age structure and location. Correlations between TRW and pMJMJ range from 0.001 (F24) to 0.62 (F5). In order to examine the possible causes of the large inter-series variability of the correlation coefficients, the influence of replication, mean age, growth rate (common period as well as the first 80 years), and latitude, on the climate correlation coefficient was tested (Fig. 5).
The chronologies of southern Finland show mean replications for the common period (1902-1978) between 18 and 120 samples. In Fig. 5a the mean replication for the series, especially when <70, are widely distributed and show no significant influence on the correlation with the climate parameter. A similar pattern is shown in figure 5b, where large differences between the lowest mean age of 23.2 years and the highest mean age of 335.8 years show very little influence on the obtained climate correlations. The influence of growth rate on these relationships is further tested in two different ways: The mean growth rate for the 1902-1978 common period (Fig. 5c) and the mean growth rate for the cambial age 1-80 (Fig. 5d). Both parameters are widely distributed and no significant pattern could be found. Figure 5e shows all tree-ring sites as black dots except for the two northernmost sites, which are plotted in grey. When including all sites, no significant influence of latitude can be found. However, a significant decrease of the climate-growth relationship is shown for the observed sites if the two sites located in the north are excluded. None of the tested statistical factors have a significant effect on the strength of the climate signal, indicating that other factors are causing the heterogeneity of the climate signal of the examined series.

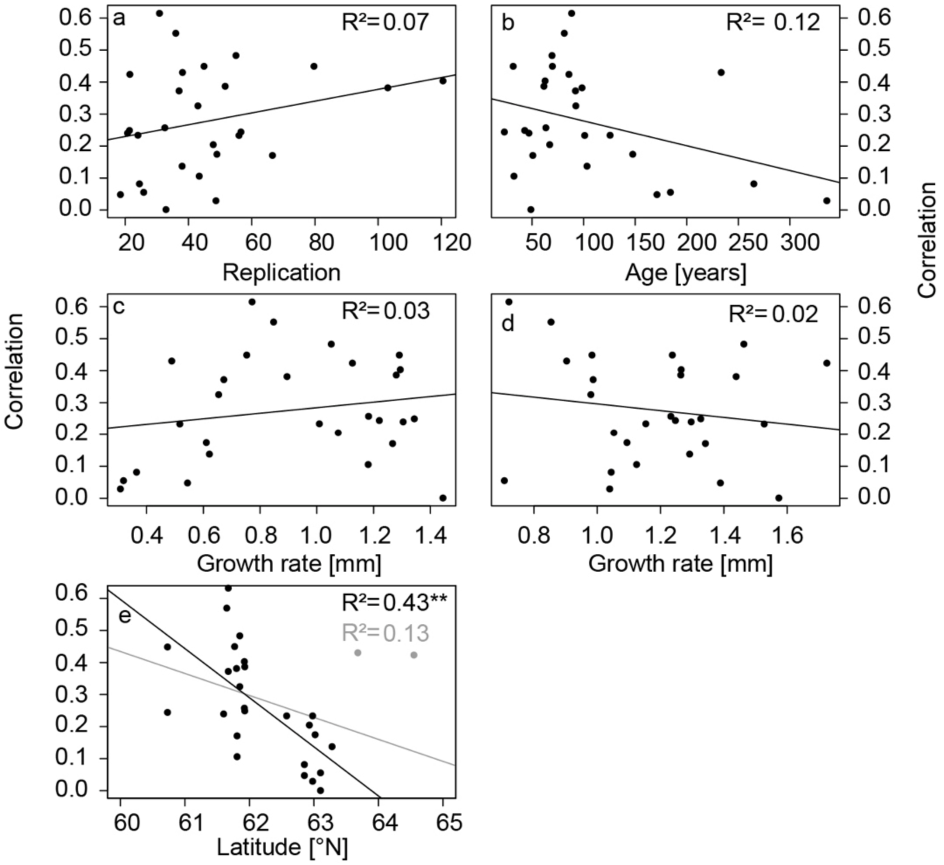

Figure 5: XY-Plots showing the pMJMJ correlations (1902-1978) of the site chronologies ordered by different chronology parameters: (a) replication, (b) age, (c) growth rate, (d) growth rate of the first 1-80 years of tree age, (e) geographical latitude.

Discussion

The relationship between tree growth and summer temperature in the northern part of Europe is considered to be very stable and thus commonly utilized for temperature reconstructions (Gouirand et al. 2008). However, the robustness and spatial extension of the climate signal in southern Scandinavia is less well understood. While several studies present drought or precipitation reconstructions from this region (Lindholm et al. 2000; Helama & Lindholm 2003; Helama et al. 2009), our analyses showed strong variations in the growth-climate response patterns among sampling sites in southern Finland. In previous studies, the strongest climate signal in tree ring chronologies is MJ precipitation (Lindholm et al. 2000; Helama & Lindholm 2003). We increased the importance of the climate signal using the sum of previous year and current year MJ precipitation.

Twenty-four chronologies from the ITRDB and four chronologies sampled in 2012, were analysed with regard to the spatial validity and the stability of the climate signal over a larger area. The climate growth relationship of pines from the 28 sites with pMJMJ showed strong variations over the common period, with correlations ranging from 0 to 0.62. To find the cause for this inhomogeneity, various parameters that may have influenced tree-growth were tested. Some uncertainties exist due to missing meta-data (e.g. pith-offset, ecological conditions) about the chronologies and the sampling design (e.g. all trees, dominant trees, age structure). The analysis also could identify the most valuable trees or sampling areas for climate-growth relationships.

The spatial distribution of sites and signals revealed no clear pattern. Though a lot of samples are from the area of Punkaharju in the southeast, the variation in climate signal in this area is large. Helama et al. (2005) showed that inter-site correlation decreases with increasing distance. However, the here tested pine chronologies do not show this trend. Chronologies from south-eastern Finland (Fig.2: sites F3-F13, F15) differed substantially, although the region is part of the Saimaa Lake Complex with comparable climate and ecological conditions. In contrast, there are sites with high inter-site correlation in spite of geographical distance (Fig. 2: F2 and F27).

The generally low inter-site correlation indicates that the coherence among site chronologies is likely associated to other parameters, such as changing micro-site conditions or the general sampling design. Therefore, the assumption that trees of the same area respond similar to a limiting climate factor does not apply here. The four micro-site chronologies (F1d, F2w, F9d, and F10w) indicate that the difference between dry and wet sites might be important for the climate signal although the difference is only significant in F1 and F2. Due to missing meta-information this finding could unfortunately not be tested for the remaining sites because there are only two other sites in the ITRDB (F3w and F13w) containing some information on micro-site conditions (marked as “lakeshore trees” and “trees sampled at the lakeshore”). Spatial and ecological components could be excluded as main factors for the heterogeneity of the climate signals. Therefore the differences should be associated with the development of the chronologies and in particular with the multiple approaches of sampling strategies.

An important parameter for the development of tree-ring time series is the replication of the chronologies. Although the replication among the examined chronologies varied substantially, all chronologies exceed a minimum sample size of 5 series, and this parameter showed no influence on the correlation with climate elements. Similarly, mean age and growth rate did not influence the signal strength of the examined chronologies. In general, the climate signal changes from the southern part of Scandinavia to the north from predominantly drought and precipitation signals toward temperature sensitivity (Lindholm et al. 2000; Düthorn et al. 2013). The spatial distribution of the tree-ring sites reaches from 60.73°N to 64.55°N, but the latitude of the sample sites showed no significant relationship with the signal strength if all samples were included. However, if we exclude the two northernmost sites we see a relatively strong relationship characterized by decreasing correlation values for precipitation with increasing latitude. However, if including all sites available in this region, only a very slight trend towards a decreasing climate signal with increasing latitude, indicating the importance of representative selection of the sites for statistical analyses.

The difficulty to determine the origin of the variation in climate signal between the different sites results in the problem of choosing a site representative for the calibration period. As the trees in southern Finland do not show the same climate signal, selecting a site with the best climate-growth relationship would likely not represent the population of pines in the region. Another important factor for climate reconstructions is time. The results presented here indicate strong temporal variations in climate signal strength. This problem also applies when updating existing historical chronologies (Tegel et al. 2010). Meta data about the location of the sampling site, the growth behavior and the chronology development are necessary information for increasing accuracy (Düthorn et al. 2013).

Conclusion

The examination of 28 TRW chronologies from southern Finland revealed strong variation in the detection of a common climate signal (temperature or precipitation) and in the manifestation of the intensity of climate-growth relationships. This study could not detect a systematic pattern of correlation coefficients, neither for large-scale spatial aspects nor for chronology development practices. This indicates that the difference among TRW chronologies has to be directly connected to site-specific aspects, including ecology and climatology. In general, this variation causes problems in the calibration of tree ring chronologies with climate targets in order to get robust spatial information for long-term reconstructions. It seems important for spatial climate reconstructions to use trees that best represent the climate-growth relationship of the investigated area. This does, however, not imply to solely consider the sites with the highest correlation if the climate signal is heterogeneous over a certain area. We therefore recommend an analysis of the historical material, e.g. origin of the wood (micro-site) and growth-climate relationship to support calibration/verification exercises. In this way, chronologies from areas where the climate signal strength is not as strong as in extreme tree-line areas, could perhaps be improved.

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Comparison of the influence of climate on tree-ring growth on different spruce species growing in different environmental conditions

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Introduction

Spruce is one of the most common and widely distributed tree species in the world. Norway spruce, Schrenk's spruce, Himalayan spruce and Siberian spruce belong to the same group of spruces (Bykov 1985). However they are located in different geographical and altitudinal regions of the word. One of the countries where Schrenk spruce found the best growing conditions is Kyrgyzstan, Schrenk spruce occupies almost all of eight forest districts. However, its stands are very fragmented and grow at different elevations, where climate factors create diversified growing conditions (Grisa and all 2008, Orlow 1989 Gan 1970,). One forest district where spruce founds favourable growing conditions is III-Fergano Czatkal (Sary-Chelek and Kang Kol Biosphere Reserve). Norway spruce is a widely distributed species in Eurasia, but in Poland, Norway spruce only occurs in theoretical range the northern and southern parts of the country.
The objective of this study was to compare two species of spruce (Schrenk spruce, Norway spruce) which grow in two different environmental conditions (Kyrgyzstan, Poland) and to study difference in their growth strategies under different pluvial conditions.

Material and methods

The study was conducted in Poland and Kyrgyzstan including three study sites, respectively. In Kyrgyzstan, the Sary-Chelek Biosphere Reserve and Kang Kol Reserve (Fig. 1) are situated on the southern slopes of Chatkal massif in the western mountain ranges of the Tien-Shan. In Poland, study sites are located in south Poland (Karpaty mountains, Tatra National Park), study places are located in Kościeliska valley and in north-east Poland in Lidzbark and Zaporowo Forest Districts (Fig 2).

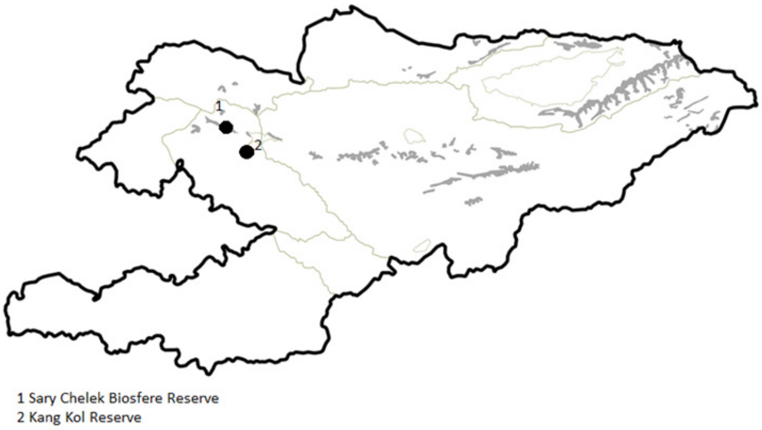

Figure 1: Map of Kyrgyzstan with 1-Sary-Chelek Biosphere Reserve, 2-Kang-Kol Reserve

Figure 2: Map of Poland: 1-Zaporowo forest district, 2- Lidzbark forest district, 3-Morskie Oko lake and Koscieliska valley

Increment cores (one per tree) were sampled from dominant and co-dominant trees. In Kyrgyzstan and in the Tatra mountains perpendicularly to the slope to minimize the effects of slope inclination on tree-ring width. In each plot 15-20 trees were sampled, located in the area.

Tree-ring widths were measured using the CooRecorder 7.3 software, and verified using CDdendro 7.3 (www.cybis.se). After COFECHA analyses, samples with low cross-correlation results were eliminated from further analyses (Holmes 1983). As a result the real chronologies (real tree rings width) have been compiled. For these chronologies, basic statistical measures of ring widths were calculated like arithmetic mean, median values, standard deviation, and mean sensitivity (Tab. 1).

Tab. 1. Characteristic of spruce's residual chronologies.

Study region	**Characteristic of residual chronologies**							
	Study site	**Elevation a.s.l**	**Data of collection data**	**Mean**	**Median**	**Standard deviation**	**Mean sensivity**	**Chronology length**
East Part of Tian-Shan Kyrgyzstan	Kang-Kol	2000 m a.s.l.	2011	1,041	0,969	0,412	0,174	1870-2011
	Sary-Chelek	1400 m a.s.l.	2010	1,010	0,965	0,309	0,179	1830-2009
South Poland	Koscieliska	1100 m a.s.l.	2011	0,979	0,969	0,150	0,106	1889-2012
	Morskie Oko	1400 m a.s.l.	2011	0,940	0,985	0,228	0,163	1904-2012
North – West Poland	Lidzbark	161 m a.s.l.	2012	0,968	0,982	0,181	0,146	1937-2013
	Zaporowo	137 m a.s.l.	2012	0,969	0,948	0,229	0,154	1953-2012

The ARSTAN software was used (Cook and Holmes 1986; Cook and Kairiukstis 1990) to develop residual chronologies by applying negative exponential curves or straight lines as detrending functions (double detrending with two different lines seems to be one of the best methods of detrending) . The standard chronologies were used for comparison of the radial increments of spruce in the analysed area (Tab 2). The residual chronologies were used to assess growth-climate (only precipitation) relationship with a linear Pearson's correlation (Pearson 1995). The significance of the observed relationships was recognized at p=0.05 level.

Tab. 2. Comparison of coincidence (p value) of chronologies thick growth of trees by t- test.)

	Morskie Oko 1400	Koscieliska 1100	Sary-Chelek 1400	Kang-Kol 2000	Zaporowo 137	Kostkowo 161
Morskie Oko 1400	x					
Koscieliska 1100	0,050409	x				
Sary-Chelek 1400	0,025010*	0,240481	x			
Kang-Kol 2000	0,192485	0,821410	0,294054	x		
Zaporowo 137	0,534331	0,334828	0,169566	0,579537	x	
Kostkowo 161	0,388375	0,331279	0,137033	0,599627	0,901366	x

- Lack of coincidence of chronologies at 0,05 significance level

Data for the analysis covered both the year of the tree-ring formation and the previous year (a total of 24 months), as well as an average representing each climatic season. Climatic conditions in the Sary-Chelek Reserve were characterized by the total precipitation obtained from the meteorological station situated in the center of the Sary-Chelek village, elevation 1100 m a. s .l, (precipitation for period 1969-2009, 40 years). In the Tatra mountains meteorological data was taken for 100 years (2009-1900) and comes from Cruts (Climat Research Unit) data base (http://badc.nerc.ac.uk/data/cru/) (Mitchell i in. 2004). Climate data used in north – east Poland comes from Kostkowo forest station (period 1988-2011) – Lidzbark Forest District Region.

Results

The longest chronology, reaching back to 1830 AD (179 years) was created from the spruce site located at 1400 m a.s.l. in Sary-Chelek Biosphere Reserve in Kyrgyzstan (Tab. 1).
The mean tree ring width shows similarity (tree rings width) among the spruce sampling sites, reaching from Kyrgyzstan 1,041 mm Kang-Kol Reserve, 1,010 mm, Sary-Chelek Biosphere Reserve, to South Poland, Koscieliska valley 0,979 mm, and Morskie Oko valley 0,940 mm and North- West Poland, Lidzbark Forest District 0,968 mm mm, Zaporowo Forest District 0,969 mm. However, differences in standard deviation were observed: Highest standard deviations occurred in the Kang-Kol Reserve and Sary-Chelek Reserve in Kyrgyzstan, the lowest standard deviation was observed in south Poland in Koscieliska valley (Tab.1).
Monthly precipitation data showed mostly positive association with tree ring growth at the Kyrgyzstan (Fig.1) sites. Positive correlations were found with winter, spring, summer and autumn precipitation prior to the year of ring formation at the 2000 m a.s.l in Kang-Kol Reserve. In the Sary-Chelek Biosphere Reserve at elevation 1400 m a.s.l., positive correlations were found with summer, autumn and winter precipitation prior to the year of ring formation (July, August, September, October, November and December) (Fig. 3). The North-West Poland site showed different growth reaction with precipitation. Significantly positive correlations were found at Zaporowo district between January precipitation in the prior year of ring formation and January, August in the year of ring formation (Fig. 4). At Lidzbark site, positive correlation was found only in August in the year of tree-ring formation. Negative correlations were observed between June precipitation of the prior year of tree-ring formation at Zaporowo, and with July and December at Kostkowo district, in current year on tree rigs formation and in September at Zaporowo District. In the south Polish sites, no significant correlations of tree growth with precipitation were found (Fig. 5). .

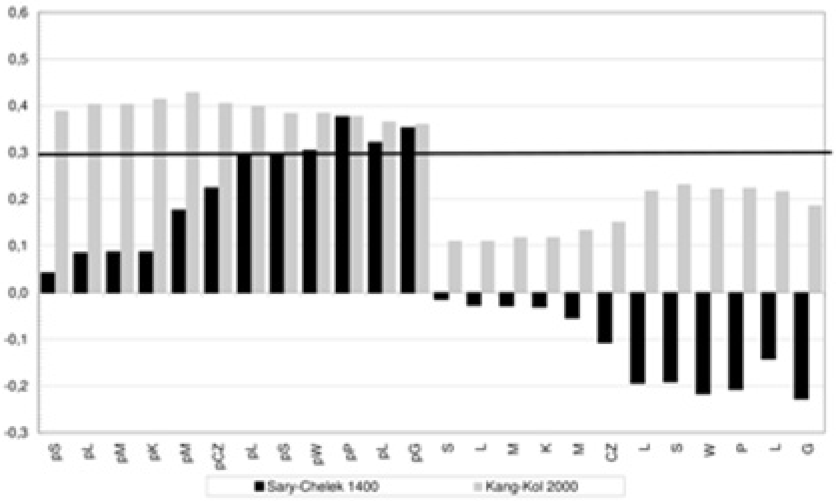

Fig. 3. Correlation between Picea schrenkiana residual chronologies and precipitation in the Sary-Chelek Biosphere Reserve and Kang-Kol Reserve. Horizontal lines indicate correlations at $p < 0.05$.

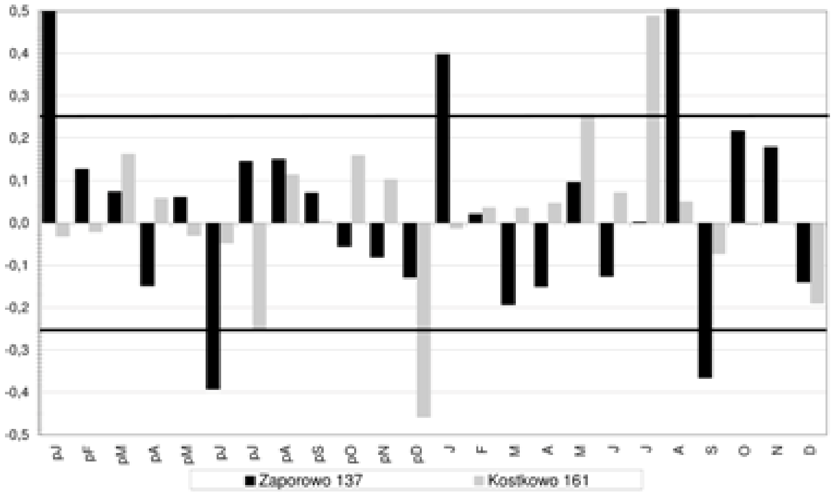

Fig. 4. Correlation between tree-ring width of Picea abies and mean monthly precipitation in Lidzbark and Zaporowo forest districts. Horizontal lines indicate correlations significant at $p < 0.05$

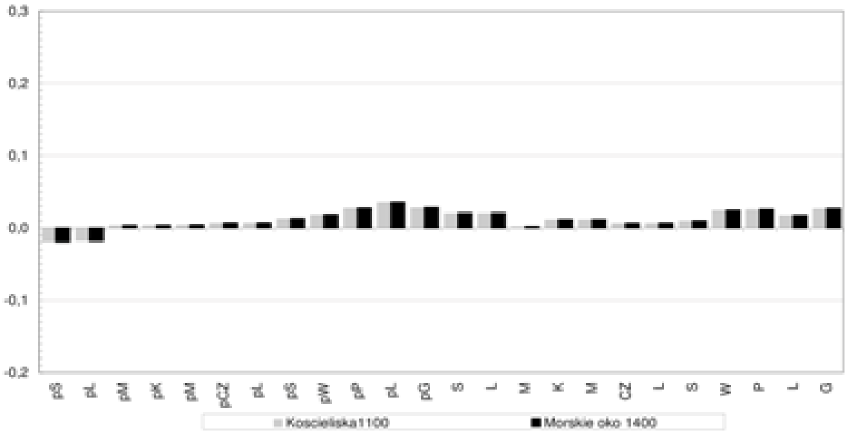

Fig. 5. Correlation between tree rings width of Picea abies trees and mean monthly precipitation in Morskie Oko lake and Koscieliska valley. Horizontal lines indicate correlations significant at $p < 0.05$

Conclusions

- The research stands from Kyrgyzstan characterized the biggest tree-ring width value, the longest chronology are also from Kyrgyzstan (Tab. 2). The Pearson correlation with tree rings and precipitation is the biggest also in Kyrgyzstan (Fig. 1).
- Characteristic of standard chronologies from all study areas are similar without chronologies between Morskie Oko 1400 & Sary-Chelek 1400 all (Tab.2)
- At study sites from Kyrgyzstan and Mazury District (Kostkowo and Zaporowo), correlation between precipitation and tree-ring width were observed (Fig 2, Fig 4), whereas at sites from the Tatra Mountains (Fig. 3) no correlation between tree-rings width and precipitation were found. This could be normal accepted on 1100 m a.s.l, but not significant reaction on 1400 m a.s.l could be created by regional conditions.

Acknowledgements

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Timing and duration of post-volcanic Northern Hemisphere cooling revealed from tree-ring records of maximum latewood density

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Introduction

Assessments of large-scale temperature responses to volcanic eruptions are important for improving our understanding of a key natural climate forcing, and more generally for understanding how changes in radiative forcings impact climate feedbacks and modes of variability. Stratospheric aerosols, the main cause of climatic perturbations associated with volcanoes, can vary in origin, size and composition. Their climatic effects may be altered by seasonality and source. Each of these factors determines the degree to which volcanic eruptions have widespread (i.e. hemispheric) impacts on climate (Robock 2000).

Reliable information about the characteristics of volcanic eruptions becomes more limited with increasing time before present. The use of proxy-records allows estimates of volcanic activity and climatic impact before the onset of meteorological observations. The sulphur concentration in ice cores is a common measure to deduce volcanic forcing by translating it into atmospheric sulphate loadings (Gao et al. 2008) or radiation equivalents (Crowley 2000).

The timing and scale of a putative climatic fingerprint is, however, difficult to estimate without using a more direct measure for temperature. Past studies (Briffa et al. 1998a, D'Arrigo et al. 2009) showed that maximum latewood-density (MXD) measurements from tree-rings indeed offer good approximations of the short-term summer cooling associated with volcanic events if the volcanic signal is extracted by averaging over several event years.

This method is nevertheless restricted to the relatively small number of well-dated volcanoes because dating errors reduce magnitude and introduce lag effects in the estimated climatic response (Esper et al. 2013). In fact, monthly dating is required if taking into account the example of a volcanic eruption around the turn of the year. Such a volcano could be assigned to two different calendar years while atmospheric dispersion and timing of the climatic response might be very similar. Ice core dates may also be affected by misdating, particularly those associated with deep-core estimates (Baillie 2008), which is an additional drawback if the most significant events are to be derived from sulphur-records.

To evaluate possible biases that may arise from such dating uncertainties, we here use a compilation of six sulphur-rich monthly dated eruptions that took place during the past millennium for comparison with MXD-based northern hemispheric (NH) summer temperature variability. Events are first analysed on a continental to hemispheric level to evaluate the lag between eruption and maximum cooling. These estimates are then used to adjust the process of averaging over multiple events. The new shape of a typical volcanic cooling pattern is tested for significance using a bootstrap approach.

Data and methods

Northern-hemispheric temperature-reconstructions

A total of 15 MXD site chronologies spanning at least 600 years were used to reconstruct summer-temperature over larger continental regions (Tab. 1). We processed each site separately and applied a power transformation (Cook & Peters 1997) and a Hugershoff detrending (Briffa et al.

1998b) to account for spread-vs.-level relationships and biological age trends. After calculating residuals from the estimated growth curves we built a robust mean for all years with a replication ≥ three series. To remove variance-changes arising from varying replication and signal strength an empirical variance-stabilization (Frank et al. 2007) was applied: we smoothed the absolute deviations from the total mean with a 200-year cubic spline and used the spline function to adjust variance. The chronologies were calibrated against gridded temperature data (Jones et al. 2012) for June-August (JJA) using the closest grid-point (Tab. 1). The common period for the calibration was set to 1926-1987, although two MXD-chronologies drop out in the late 1970s. To retain the full temperature variance a scaling was performed in order to translate tree-ring indices to temperature means (Esper et al. 2005). Since all proxy-records explained a significant amount of local temperature variation (Tab. 1), all site-records were averaged in order to estimate large-scale anomalies. Continental averages were calculated for North America, Europe and Asia using 4, 7 and 4 site-chronologies, respectively. Additionally a simple northern hemispheric average was built as the arithmetic mean of the 3 continental records. Here, we exclusively focus on close-ups for six volcanic events between 1600 and 1883.

Table 1: Tree-ring sites and measures of replication for the 1580-1903 period. The corresponding grid-points refer to the CRUTEM4-dataset, which was used for calibration. The Pearson-correlation between tree-ring data and summer temperature is given as r_{MXD_JJA}.

Site name	***Continent***	***Location***	***Replication***		***Corresponding grid-point***	r_{MXD_JJA}	***Reference***
			Mean	***Minimum***			
Alaska	N-America	68.8N/-142.4E	75	47	67.5N/-132.5E	0.53	Anchukaitis et al. 2013
Altai	Asia	50.2N/90.0E	17	15	52.5N/87.5E	0.62	Myglan et al. 2012
Athabasca	N-America	52.3N/117.3E	28	8	52.5N/-117.5E	0.47	Luckman et al. 1997
Campbell	N-America	68.3N/-133.3E	19	14	67.5N/-132.5E	0.32	Schweingruber, ITRDB
Jaemtland	Europe	63.5N/15.5E	31	14	62.5n/17.5E	0.64	Schweingruber et al. 1988
Lauenen	Europe	46.4N/7.3E	23	11	47.5N/7.5E	0.39	Schweingruber et al. 1988
Lötschental	Europe	47.5N/7.5E	58	44	47.5N/7.5E	0.60	Büntgen et al. 2006
Mangazeja	Asia	66.7N/82.3E	36	3	67.5N/82.5E	0.60	Briffa et al. 2001
Nscan	Europe	67.5N/22.5E	50	29	67.5N/22.5E	0.80	Esper et al. 2012
Polarural	Asia	66.9N/65.6E	30	10	67.5N/67.5E	0.81	Briffa et al. 1995
Pyrenees	Europe	42.5N/2.5E	70	62	42.5N/2.5E	0.40	Büntgen et al. 2008
Quebec	N-America	57.5N/-76.0E	15	7	57.5N/-77.5E	0.69	Schweingruber 2007
Torneträsk	Europe	68.2N/19.7E	26	11	67.5N/17.5E	0.83	Melvin et al. 2013
Tyrol	Europe	47.5N/12.5E	35	16	47.5N/12.5E	0.38	Esper et al. 2007
Zhaschiviersk	Asia	67.5N/142.6E	21	14	66.3N/143.8E	0.27	Briffa et al. 2001

Superposed epoch analysis

A common tool to assess the quantity of volcanic cooling is the superposed epoch analysis (SEA; Panofsky & Brier 1958) that averages temperature patterns after a certain number of events. Including at least 10 years prior and 20 years after the volcanic events allows comparing pre- and post-volcanic time-series characteristics and ensures full coverage of the retention period. Herein all SEAs are displayed as anomalies to the ten pre-volcanic years (lag-10 to lag-1). The year of eruption is referred to as the reference point and located at year zero in the SEA. Since this study focuses on timing and duration of the climatic response, we filtered out the (1) climatically most relevant and (2) well dated volcanic events during the last 800 years - reflecting the original length of the temperature reconstruction.

(1) In a first step an ice-core sulphur record (Gao et al. 2008) was used to identify the most relevant events. The sulphur-record features a global, northern and southern hemispheric

sulphate-loading time-series. The 20 highest peaks were chosen not only from the northern hemispheric record but also from the global one (Tab. 2). Proceeding only with those events that were recorded in both records ensures that high-latitudinal events close to the arctic ice sheet depositions are not misinterpreted. (2) The remaining peaks were compared with a list of monthly dated volcanoes (Siebert et al. 2010). If no major eruption (volcanic explosivity index ≥ 4) was documented in the same year or one year prior, the event was rejected. The others were assigned to a volcano name and region (Tab. 2).

Table 2: Selection of volcanic events over the last 800 years. Only six out of sixteen globally relevant eruptions could be identified as a monthly dated event.

Gao2008		***Month of eruption begin***	***Volcano name***	***Volcano region***
Glo	***NH***			
1227	1227	-		
1258	1258	-		
1275	-			
1284	1284	-		
1328	1328	-		
1341	-			
1452	1452	-		
1459	1459	-		
-	1476			
1584	1584	-		
1600	1600	Feb	HUAYNAPUTINA	Perú
1641	1641	Jan	PARKER	Philippines
1693	-			
1719	1719	-		
-	1729			
1783	1783	Jun	GRIMSVÖTN	Iceland
1809	1809	-		
1815	1815	Apr	TAMBORA	Indonesia
1831	1831	-		
1835	1835	Jan	COSIGUINA	Nicaragua
1883	1883	Aug	KRAKATAU	Indonesia
-	1912			
-	1925			
1963	-			

To assess the significance of post-volcanic temperature patterns a bootstrapping technique was employed (Zanchettin et al. 2013). The actual set of six event-years was replaced 1000 times by a set of six randomly chosen years between 1580 and 1903. By calculating SEAs with these random years instead of those containing volcanic events the probability distribution of temperature anomalies can be quantified for each time step. Deviations from the 95 and 99 percentiles of this distributions indicate a significant temperature anomaly.

Results

The two sets of 20 maximum sulphate loadings – global and northern hemisphere – show an overlap of 80% (Tab. 2). Among all 16 common years only six could be assigned to a monthly dated volcano from the record in Siebert et al. (2010). Although the 20 biggest spikes in the sulphur records are evenly distributed over the 800 years of record, all of these six dated events took place in the second half of the millennium. This indicates either incompleteness in the documentary volcano record or dating uncertainties in the ice core records. However, it limits our analyses to the recent half of the record. Despite the 1783 Grimsvötn eruption, the remaining events are of tropical origin, which is fundamental for a widespread and even distribution of volcanic ash over both hemispheres (Budner & Cole-Dai 2003).

The spatial distribution of long-density records is somewhat weighted toward Europe regarding the total number of sites and their individual replication (Tab. 1). On average, European sites also correlate strongest with summer-temperature (r_{ave} = 0.58) for the 62 years of calibration period.

However, sites in North America and Asia also contribute strongly to the amount of explained temperature variance (r_{ave} = 0.51 and 0.57, respectively). While local records are strongly driven by internal climate variability and regional characteristics, these fractions tend to level out if the scale is increased. In hemispheric or continental averages volcanic forcing is unmasked and often leaves a distinct cooling peak (Jones et al. 2003). This is also observed for the climatic effect of the six volcanoes studied herein. While the most negative NH temperature anomalies in the six epochs analysed can be attributed to the volcanic events in five of six cases (either at lag0 or at lag1) the continental records show a number of similarly cold years before or after the actual cooling period (Fig. 1).

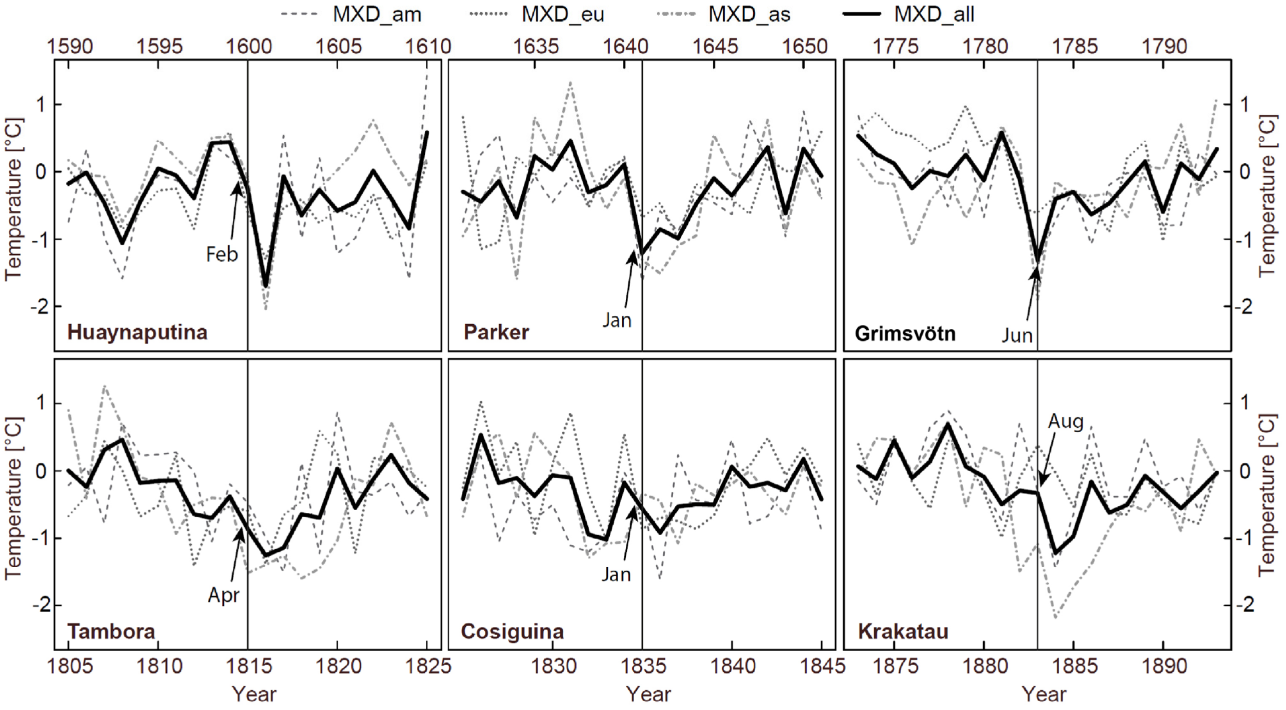

Figure 1: Epochs of strong volcanic events as revealed by continental and hemispheric summer-temperature reconstructions. Temperatures represent anomalies with respect to the 10 years prior to the event. Vertical lines in the middle of each epoch indicate the year of the sulphur-peak in the ice-core records. Arrows give the eruption month as derived from documentary evidence.

Although volcanic cooling is an outstanding feature in these epochs, it varies strongly in timing, magnitude and shape. Temperature decreases mostly abruptly, but is either followed by immediate retention (e.g. after Huaynaputina and Grimsvötn) or it takes two to three years to recover to the original level (e.g. after Mt. Parker, Tambora or Krakatau). The lowest values for hemispheric temperature occur in the year of the sulphur peak or one year later. However, there is no consistent pattern that links this lag to the month of eruption. Eruptions during winter, for instance, can result in a different timing for minimum summer-temperature (Mt. Parker vs. Huaynaputina and Cosiguina). The Grimsvötn eruption in contrast shows maximal summer cooling in 1783 although the ejection of ash does not start before June of the same year. If a mean magnitude is to be derived from these events, such lag-effects result in blurring of the cooling pattern.

To estimate the effect of seasonal transportation patterns and resulting lag-structures, SEAs were calculated in two different ways: (1) For SEA1 the documented years of eruption (which match the years of sulphur peaks) were used as the reference point in the centre of the SEA. (2) In a second approach (SEA2) the reference points were synchronized with the years of minimum post-volcanic summer-temperature in order to estimate the maximum cooling effect. According to Figure 1 these are the years 1601, 1641, 1783, 1816, 1836 and 1884. The resulting SEAs for continental and hemispheric averages show distinct differences in magnitude and timing of post-volcanic cooling

(Fig. 2). After adjusting the reference points the temperature drop is now observed at lag 0 with a rather sharp drop. Only in the European SEAs a clear pattern is missing and cooling is only weakly significant against random fluctuation. The bootstrap-bands are a robust estimate of variance for the SEAs and all values before and after the volcanic spikes stay within the limits of the 99 percentile. The positive effect of averaging regarding the signal-to-noise ratio becomes apparent in a significantly reduced bandwidth for the hemispheric SEAs. The reference period for the calculation of anomalies is also accompanied by a slightly smaller bandwidth, especially for the Asian SEAs.

With respect to the standard error of the mean the most significant cooling is found for the northern hemispheric SEA2 with a temperature difference of 0.93°C between lag -1 and lag 0. This value is smallest for Europe with only 0.44°C.

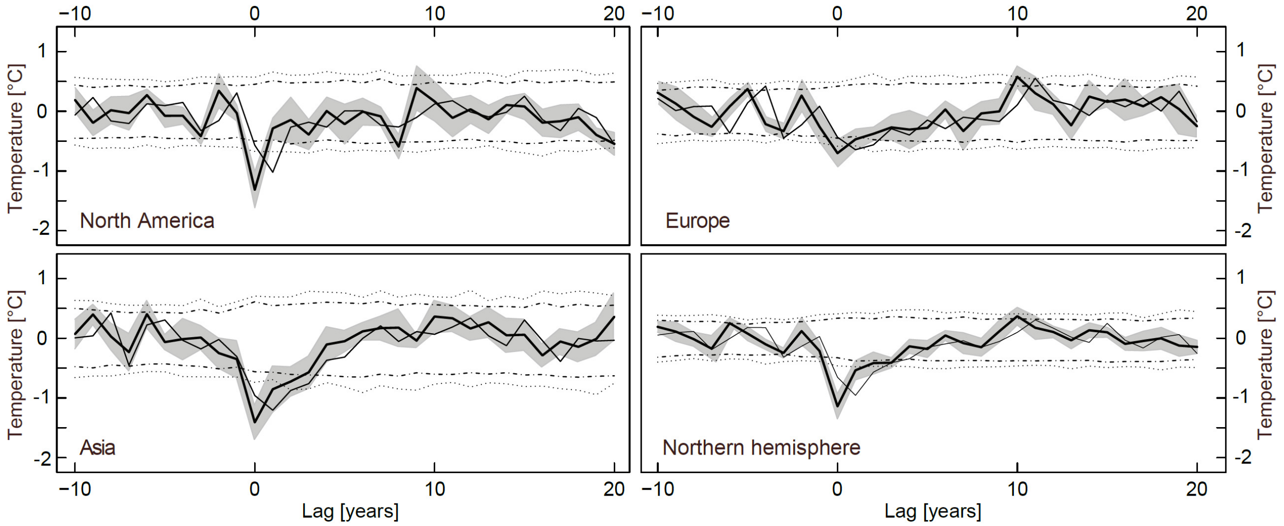

Figure 2: SEAs for different continental averages and the Northern hemisphere. The bold lines represent SEA2 with epochs centred around 1601, 1641, 1783, 1816, 1836 and 1884. SEA1 (thin lines) used the documented/sulphur record years 1600, 1641, 1783, 1815, 1835 and 1883. Temperatures represent anomalies with respect to the 10 years prior to the event. Dashed lines indicate the 95 and 99 percentiles of a bootstrap approach to assess significance. The grey bands show the standard error of the mean (standard deviation divided by the square root of the sample size) for each time-step.

Discussion

This study documents the potential of MXD-data in storing the climatic response to volcanic eruptions, which is an important information regarding the calibration of sulphur-records and climate models. Although the number of events studied herein had to be limited due to methodological reasons we found distinct patterns of post-volcanic cooling with the help of averaged SEAs. At the same time the basic need for a detailed analysis of single events was revealed. Despite the influence of other climate forcing parameters and internal variability the volcanic impact resulted in a cooling in all 6 epochs and allowed for an improved alignment according to the cooling pattern. This alignment had to follow a visual inspection of the single temperature time-series because no robust relationship between the seasonality of the eruption and the offset between eruption and cooling could be established. Climatic responses are observed in the next growing season or in that of the following year. Only the high-latitudinal eruption of Grimsvötn in summer 1783 translates in immediate cooling whereas magnitude and duration of the cooling associated with this event are in line with eruptions of tropical source.

Compared to other studies (Briffa et al. 1998a, D'Arrigo et al. 2009), the observed cooling-response in SEA2 for North America, Asia and the hemisphere is fairly strong in magnitude. To some extent this is caused by the new approach of aligning by the climatic impact, but it is also a corollary of using only the 6 biggest events. While these SEA2s show temperature anomalies of more than -1°C, the European SEA2 is only weakly significant. This can be attributed to the large portion of alpine records, which respond less to volcanic forcing (Esper et al. 2013).

The two- to three-years temperature depressions in the SEA1s suggest a slow emergence of volcanic cooling with the minimum temperature observed at lag1 after the eruption. In fact, this pattern is an artefact of shifting seasonality, which should be considered in the interpretation. In a larger setup with more volcanoes this approach could, however, help to quantify the number of volcanoes with response at lag0, lag1 or lag2.

According to theoretical sulphur transport (Gao et al. 2008) and observational data of atmospheric optical depth (Crowley et al. 2013) it is more likely to find a sharp temperature decline with a subsequent - possibly fast - recovery. This concept would be better in line with the pattern that was found for the SEA2s and justifies the adjustment of the temperature-minima. Irregular lag-structures, however, limit the potential to upscale this approach by incorporating more monthly dated volcanic events. But using a simple temperature-minimum between lag0 and lag2 as reference point – as in this study – solves the problem although it might introduce a bias in the adjustment procedure if noise or internal variability alter the volcanic signal.

Conclusion

This study presents a data-adaptive way of analysing the volcanic impact on temperature records across the NH. The method suggests results that are considerably different from previous studies concerning both duration and magnitude of post-volcanic cooling. Adding more volcanoes of smaller size will likely mitigate the increased magnitude. The shape of the climatic response shows an abrupt temperature drop and a short recovery period. Since the alignment of volcanic impacts followed a visual inspection, it would be desirable to objectify this step. The high quality and spatial coverage of the underlying database indicate that the detection of cooling patterns can potentially be automated by applying objective detection algorithms (Hendry & Pretis 2013). This would help to expand this method to more advanced climate time-series and an extended set of volcanoes, which would likely result in more significant results.

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Do oxygen isotopes in tree rings from coastal Alaska record atmospheric circulation patterns?

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Introduction

Oxygen isotopes in tree-rings have demonstrated abilities in providing valuable information on past climate variability, and notably large-scale atmospheric circulation dynamics. In addition to ecophysiological processes such as transpiration, variations in $\delta^{18}O$ of tree-ring cellulose mainly reflect variations in $\delta^{18}O$ of source water acquired by trees and therefore can be linked to the hydrological cycle and transport of air masses (Evans and Schrag, 2004; Poussart et al., 2004; Raffalli-Delerce et al., 2004; Masson-Delmotte et al., 2005; Miller et al., 2006; Treydte et al., 2006; Treydte et al., 2007; Saurer et al., 2008; Brienen et al., 2012; Saurer et al., 2012).

Studies of climate variability are important in high latitude regions such as Alaska because they are particularly sensitive to climate change. According to the IPCC AR4, average Arctic temperatures increased by almost twice the global average during the past 100 years (IPCC, 2007). Yet, the mechanisms responsible for this warming are not fully understood. Some studies have suggested that continental warming may be driven to some degree by oceanic processes rather than anthropogenic influence on the greenhouse/radiative balance of the earth (Compo and Sardeshmukh, 2009). Adding to this uncertainty, the degree to which the oceans themselves have recently warmed due to internal multi-decadal variability and other natural and anthropogenic forcings is still unclear (Compo and Sardeshmukh, 2009; Doney et al., 2012). Thus, improving the knowledge of local and regional climate variability and large-scale atmospheric circulation dynamics particularly in high latitude oceanic regions as the Gulf of Alaska (GOA) is of high relevance.

The aim of this project was (*i*) to develop a 350-year tree-ring width chronology and the first centennial-long tree-ring (112-year) cellulose $\delta^{18}O$ chronology of *Tsuga mertensiana* from south coastal Alaska and (*ii*) to test the potential of these tree-ring parameters to record local climate variability and large-scale atmospheric circulation patterns.

Study site

The study site is located near Seward (Kenai Peninsula, southern Alaska, 60°07′28″N 149°26′00″W, 358 - 544 m a.s.l. (Fig.1)). The forest type is a temperate rainforest under a strong maritime influence. The dominant tree species are Sitka spruce (*Picea sitchensis*) and mountain hemlock (*Tsuga mertensiana*).

The nearest weather station is at Seward Airport (60°12’N 149°45’, 59 m a.s.l.) with temperature and precipitation data available for the period from 1908 to the present. According to the Western Regional Climate Center (period: 1949-2005, http://www.wrcc.dri.edu/), Seward has a mean annual precipitation of about 1730 mm with a maximum in September. Mean annual minimum and maximum temperatures are 1.2°C and 7.6°C, respectively, with average daytime winter temperatures above freezing (Shulski and Wendler, 2007).

The climate in the Northeast Pacific region is primarily driven by the Aleutian Low pressure system during winter and spring, whereas the North Pacific High pressure system dominates in the GOA region in summer (Wiles et al., 1996; Wiles et al., 1998; Wilson et al., 2007).

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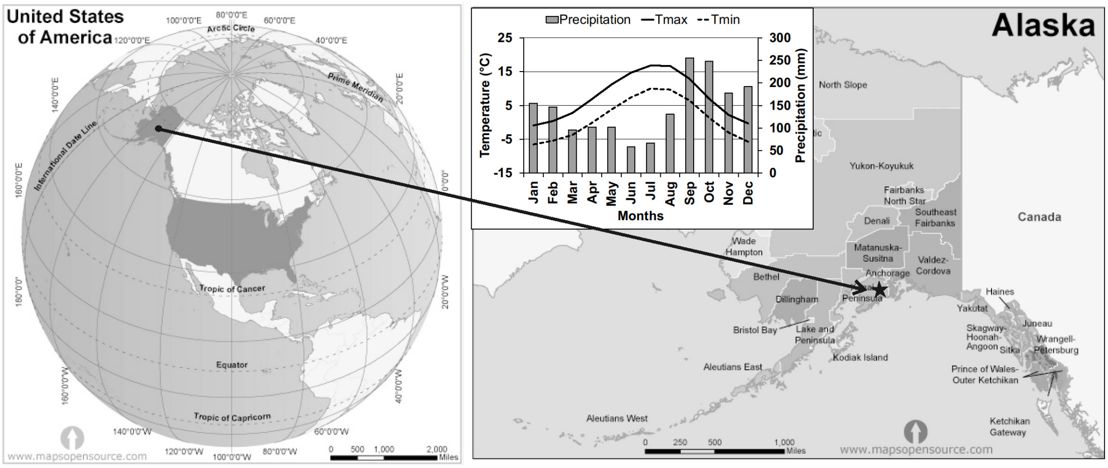

Fig. 1. Location of the study site in the USA and Alaska (black star) and seasonal distribution of precipitation (bars), maximum temperature (solid line) and minimum temperature (dashed line) at Seward (average 1949-2005). Map source: http://www.mapsopensource.com/; Climate data source: Western Regional Climate Center: http://www.wrcc.dri.edu/.

Large-scale atmospheric circulation patterns linked to the variability of the Aleutian Low include the *Pacific/North American* (PNA) and *the North Pacific pattern* (NP). The PNA is a feature that is evident in the weather pattern with zonal flow (flow along latitudinal lines) for the positive phase, when the Aleutian Low is deeper by an average of 10 to 15 mbars, while during the negative PNA mode the Aleutian Low elongates across the Bering Sea (Shulski and Wendler, 2007). Another prominent feature is *the Pacific Decadal Oscillation* (PDO is the leading mode of October-March sea surface temperature variability poleward of 20° (Mantua et al., 1997). All these features are well correlated with regional temperature and precipitation in the Northern Pacific (Hartmann and Wendler, 2005).

Data and Methods

Two increment cores per tree were sampled at breast height from 24 living mountain hemlocks between 358 m and 544 m a.s.l. using a regular increment borer (⌀ = 5 mm). This tree species was chosen due to the dominance at various altitudes. After tree-ring width measurements and cross-dating in COFECHA, 48 individual tree-ring series were generated with the age trend removed with a negative exponential function in ARSTAN. A 350-year (1662-2011 AD) tree-ring width chronology (TRW) was developed "$\text{TRW}_{\text{Lost Lake}}$".

Subsequently, four trees (eight increment cores in total) were selected for δ^{18}O isotope analysis based on the series' length and highest inter-series correlation. Individual annual rings for the period 1900-2011 (112 years) were split with a scalpel under a stereo microscope *Leica WILD M3B* (Leica Microsystems GmbH, Wetzlar, Germany). The rings from two cores of each tree were pooled to obtain enough wood for oxygen isotope analysis. After weighing, the samples were divided into two groups: with the masses < 16 mg (group 1) and > 16 mg (group 2). Due to high variability in weight of the tree ring material two different methods of homogenization were applied. The samples from the first group were homogenized with an ultrasonic treatment *Bandelin SONOPLUS HD3100* (Bandelin electronic GmbH & Co. KG, Berlin, Germany) after cellulose extraction, while the samples from the second group were mechanically ground with an ultra centrifugal mill *ZM200* (Retsch Technology GmbH, Haan, Germany; mesh size of the sieve: 500 µm) before cellulose extraction, i.e. chopped with subsequent sieving. Cellulose from both groups was obtained by applying a standard extraction procedure based on Boettger et al., 2007, which is a modification of the method developed by Sohn and Reif in 1942 (Sohn, 1942; Boettger et al., 2007). Ultimately, between 0.65 and 1.3 mg of all the samples was weighed into tin capsules.

Isotope ratios were measured with an Elemental Analyzer, *EuroVector Euro EA3000* (Hekatech, Germany), coupled with an Interface *Finnigan ConFlo III* (Thermo Scientific, Germany) to an Isotope Ratio Mass Spectrometer, *Delta V Advantage* (Thermo Scientific, Germany). Finally, the first centennial tree-ring cellulose chronology from coastal Alaska at the Lost Lake site (1900-2011 AD) was developed "$\delta^{18}O_{\text{Lost Lake}}$".

Climate data from Seward (period: 1908-2011) and gridded datasets of the Climatic Research Unit (CRU TS 3.10) for the period 1901-2009 were tested against each other and the CRU datasets were used for further analysis, because of gaps of several months and years in the Seward station records. In addition, for the correlation analysis between tree-ring parameters and large-scale atmospheric circulation patterns we used mean monthly regional sea surface temperatures from the Hadley Centre (HadISST1 data set) and monthly and annual indices of the Pacific Decadal Oscillation (PDO) from the Joint Institute for the Study of the Atmosphere and Ocean, University of Washington for the period 1900-2011 (http://jisao.washington.edu/pdo/) (Mantua et al., 1997). All the climate data were downloaded from the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer research tool (http://climexp.knmi.nl/) (Trouet and Van Oldenborgh, 2013).

All available mountain hemlock chronologies from south coastal Alaska which were used for the spatial correlation analysis were from the International Tree-Ring Data Bank (ITRDB) of the National Oceanic and Atmospheric Administration (NOAA) Paleoclimatology Program and World Data Center for Palecoclimatology (http://www.ncdc.noaa.gov/paleo/treering.html). These datasets were also standardized with a negative exponential function in ARSTAN for comparison with the $\text{TRW}_{\text{Lost Lake}}$.

Climate calibration analyses were performed for both tree-ring parameters based on the following climate variables: monthly minimum, mean, maximum temperatures, precipitation, relative humidity, vapour pressure and cloud cover from April of the previous year to September of the current year including combinations of different months. Here we only present the results of the strongest correlating parameters temperature and precipitation.

Results

Chronology characteristics

The mean EPS of the $\text{TRW}_{\text{Lost Lake}}$ over the whole period is 0.91 (Fig. 2), thereby exceeding the commonly used threshold of 0.85 (Wigley et al., 1984) after the year 1770 until present. A mean inter-series correlation (rbar) of 0.36 indicates these trees contain a common external forcing well represented by the site level data (Cook et al., 1990).

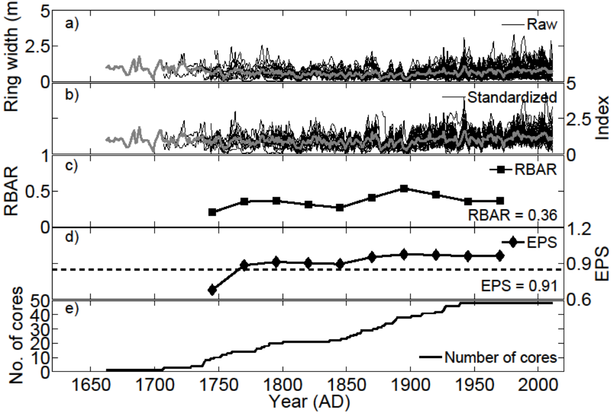

Fig. 2. Plots of raw and standardized tree-ring width data RBAR, EPS and sample replication: (a) Individual (black) and average curves (grey). (b) Individual ring-width indices (black) and final Lost Lake tree-ring chronology (grey). (c) 51-year running RBAR. (d) EPS. (e) Number of cores.

The spatial robustness of the $TRW_{Lost\ Lake}$ was tested by comparison with other available mountain hemlock chronologies from south coastal Alaska for the common period of overlap 1662-2002 (341 years) (Fig. 3). In general, the $TRW_{Lost\ Lake}$ correlates significantly with other chronologies from the region ($p < 0.01$, $n = 341$). With two exceptions, the values of the correlation coefficients are particularly high within 500 km ($r > 0.46$). This indicates a common variability in annual and long-term growth among different sites in this area. We speculate that two sites with lower correlations are due to altitudinal differences and different geomorphological and/or microclimatic conditions related to glacier influence.

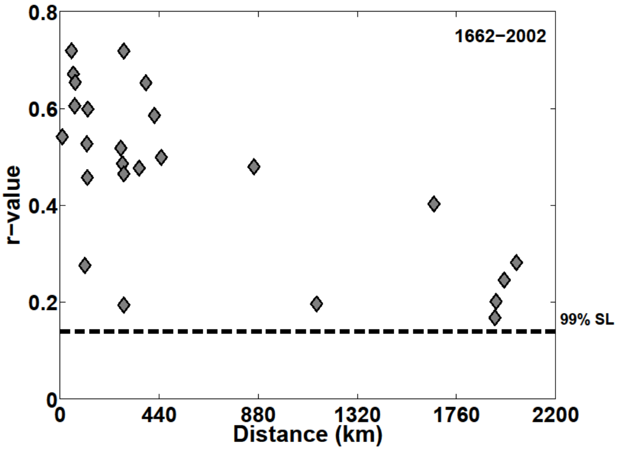

Fig. 3. Pearson's correlation coefficients between Lost Lake and other chronologies from south coastal Alaska for the period 1662-2002 (341 years) as a function of distance in km. The black dashed line indicates the 99% significance level, n = 341.

Values of the $\delta^{18}O_{Lost\ Lake}$ in tree rings of individual trees vary between 20.02 ‰ and 26.42 ‰ (with a mean of 23.46 ‰, SD=0.87 ‰). The mean RBAR is 0.72 and the EPS is 0.91 indicating strong and temporally stable coherence between individual trees for the 1900-2010 period. Thus, consistent with earlier publications, four individual trees are sufficient to represent the study site (Leavitt and Long, 1984) (Fig. 4). Notably, the correlations are approximately equally strong for the unfiltered, and high and low-pass filtered data.

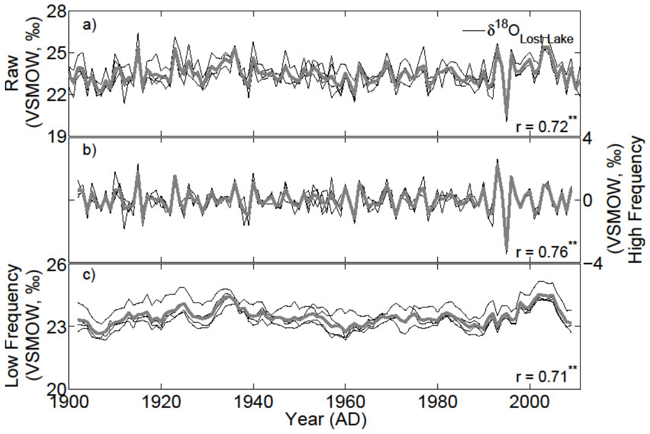

*Fig. 4. Tree-ring cellulose $\delta^{18}O$ data: (a) Raw individual (black) and average curves (grey). (b) 5 year high pass filtered. (c) 5 year low pass filtered. The corresponding rbar values are provided for each frequency domain: **p < 0.01.*

Response to local/regional climate variability

Generally maximum temperatures seem to be the dominant driver of tree growth based on statistical relationships between the $TRW_{Lost\ Lake}$ and monthly climate variables. Overall, the thermal conditions of the previous and current spring growing seasons are most relevant for tree growth (Fig. 5, left). During the whole study period (1902-2009) highest correlations are seen in May (r =

0.53) and from April to July (r = 0.47). Precipitation seems to be less important compared to temperature (maximum r-values: -0.27 in May and -0.26 from April to July; $p<0.05$, n = 110).
The $\delta^{18}O_{\text{Lost Lake}}$ also correlates highest to maximum temperature with comparable r-values to TRW. However, the highest correlations are restricted to the current summer (Fig. 5, right), with highest r-values in July (r = 0.44) and the combination of June-July (r = 0.44). Similarly to correlations with temperature, significant r-values with precipitation are also seen in July (r = -0.22) and June-July (r = -0.30), ($p<0.05$, n = 110).

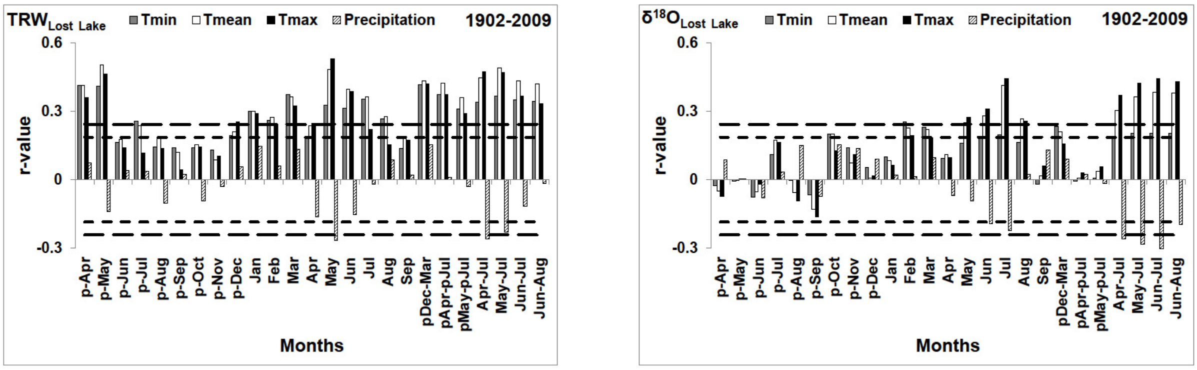

Fig. 5. Pearson's correlation coefficients between the Lost Lake chronology and monthly temperatures and precipitation for the period 1902-2009: (left) Tree-ring width. (right) Tree-ring cellulose $\delta^{18}O$. The black dashed lines indicate the 95 % (thin) and 99% (thick) significance levels.

Response to large-scale climate variability

To test the potential of both tree-ring parameters for large-scale climate reconstruction, calibration analysis was performed with monthly PDO indices and regional SSTs on a monthly basis and combinations for the period 1901-2011. Highest correlations of both tree-ring parameters are found from June to August of the current year with stronger relationships between the $\delta^{18}O_{\text{Lost Lake}}$ and PDO compared to the $TRW_{\text{Lost Lake}}$. Results for SSTs were similar, but they are not shown here. (Fig.6). This holds, however, only for the raw and the high frequency domain in particular (r = 0.46, $p < 0.01$, n = 110). At the low frequency domain $TRW_{\text{Lost Lake}}$ shows stronger similarities to PDO (r = 0.34, non-significant) compared to the $\delta^{18}O_{\text{Lost Lake}}$, which does not correlate at all (r = 0.18, non-significant).

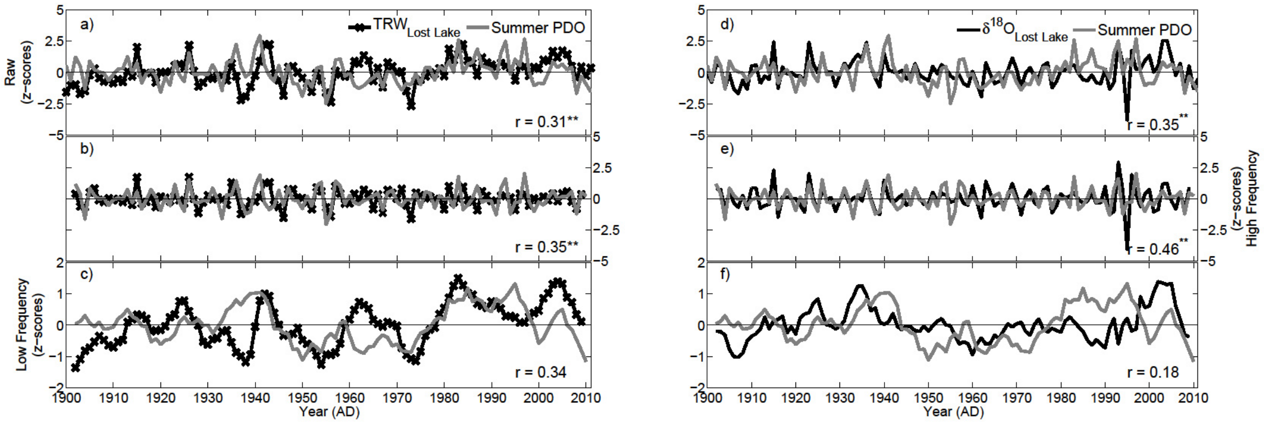

Fig .6. Time series of the Lost Lake tree-ring width (left) and tree-ring cellulose $\delta^{18}O$ (right) chronologies vs. summer Pacific Decadal Oscillation index (June to August) at different frequency domains: (a, d) Raw. (b, e) 5-year high pass filtered data. (c, f) 5-year low pass filtered data. The corresponding correlation values are provided for each frequency domain: $^{**}p < 0.01$.

Discussion and Conclusions

Response to local/regional climate variability

Spring/early summer temperatures are the most important factors controlling the radial growth and therefore photosynthetic and cambial activity at our study site. These relationships to temperature are consistent with other studies from Alaska which also found a strong positive response to warm-season, spring and summer temperatures (Briffa et al., 1992; Wiles et al., 1996; Wiles et al., 1998; Barber et al., 2004; D'Arrigo et al., 2004; Wilson et al., 2007). However, we also found that temperatures from previous December to current March are important for tree growth at our site as well. Similar results have been observed with different conifers in Northwestern US (Fritts, 1965) and Northern Siberia (Lloyd et al., 2011). It was also shown that tree growth in Eastern Siberia mainly depends on soil hydrothermal conditions (Nikolaev et al., 2009). These studies found that the cambium activity was delayed by long and cold winters and in some cases a lack of snow cover resulted in deep-freezing of soil. The latter especially affects conifers being physiologically active during winter, which might also be the case at our study site.

The positive correlation between δ^{18}O in tree rings and mid-summer maximum temperature (June-July, over the period 1902-2009) is likely a combined influence of the isotope values in the source water (precipitation and soil water) and leaf-water enrichment due to transpiration, which are both temperature dependent. Similarly the highest correlations of the latewood δ^{18}O in tree rings of *Abies alba* Mill. from the Swiss Jura mountains with maximum temperature during the vegetation period has also been observed before (Rebetez et al., 2003), particularly during rainy days, implying that the isotopic signal in tree-ring cellulose is mainly provided by the source water signal (Rebetez et al., 2003). However, variations of δ^{18}O in tree rings are difficult to explain by temperature variability alone. Water in plant tissue has the same isotopic signal as the source water – until it reaches the crown, where fractionation due to evapotranspiration takes place. The strength of evaporation depends on variations in stomatal conductance and therefore on vapour pressure deficit. Our analysis, however, is restricted by reduced data availability of climate variables such as relative humidity, cloud cover and vapour pressure, and also data of δ^{18}O in precipitation which often correlates highest to tree-ring δ^{18}O (Reynolds-Henne et al., 2007; Brienen et al., 2012).

Response to large-scale climate variability

Highly significant positive correlations were found between TRW and PDO and regional SSTs respectively with the PDO pattern being closely linked to and mainly driven by Pacific SST variability (Mantua et al., 1997; Zhang et al., 1997). The SST signal was, however, more prominent. There exist numerous previous studies of large-scale climatic variability and shifts based on tree-ring width data in the Northern Pacific region and the Gulf of Alaska (Blasing and Fritts, 1976; Wiles et al., 1998; D'Arrigo et al., 1999; Biondi et al., 2001; D'Arrigo et al., 2001; Gedalof and Smith, 2001; MacDonald and Case, 2005; D'Arrigo and Wilson, 2006; Wilson et al., 2007). A challenge with these studies is that they often do not agree prior to the instrumental period. Interdecadal oscillations in tree-ring based reconstructions of SSTs were generally in good agreement with multi-decadal variability in the Aleutian Low intensity (Wiles et al., 1996; Wiles et al., 1998; Wilson et al., 2007).

At our site, summer, as well as annual PDO indices, correlate more strongly with the $\delta^{18}O_{\text{Lost Lake}}$ in the high frequency domain than with TRW. However, it remains, unclear why correlations between the $\text{TRW}_{\text{Lost Lake}}$ and the summer (June to August) and annual PDO indices are still significant while the PDO signal in $\delta^{18}O_{\text{Lost Lake}}$ weakens for the low frequency domain. Recently, Kipfmueller et al. presented a set of tree ring based reconstructions of the PDO to test if the choice of reconstruction method influences the association between the PDO and forest fires in the western United States (Kipfmueller et al., 2012). They concluded that, even though, much efforts have been directed at producing proxy-based reconstructions of the PDO index, the behaviour of the PDO prior to the

20th is still uncertain. There is a good agreement among all the reconstructions during the instrumental period. However, the large discrepancies before the calibration period suggest limitations in quantifying the pattern at both high and low frequencies during the 18th and the 19th centuries. It thus remains a research priority to obtain a consensus regarding the temporal evolution and spatial structure of low-frequency behaviour in the north Pacific prior to 1900 (Kipfmueller et al., 2012). Our chronology has demonstrated some potential to use oxygen isotopes in tree rings to understand pre-industrial climate variability in the Pacific. However, the long-term relationship between $\delta^{18}O$ and the PDO pattern at our site is not well understood. Seasonal sampling of soil/twig/needle samples might help for better understanding of isotopic fractionations in this ecosystem and their relationship to environmental factors. We propose that expanding the spatial (and temporal) coverage of $\delta^{18}O$ records from coastal sites in the Northern Pacific will be crucial to test basin-wide climate drivers, and thus the abilities of oxygen isotopes in tree rings to serve as a proxy for North Pacific climate variability.

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SECTION 3

ECOLOGY
&
FOREST MANAGEMENT

Using dendrochronology to characterize forest disturbance by mountain pine beetle

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Introduction

Mountain pine beetles, *Dendroctonus ponderosae* Hopkins (MPB) are a natural disturbance of North American pine forests, and outbreaks play an important role in directing ecological processes and maintaining the biological diversity of forest ecosystems. However, having infested about over 13 million hectares of lodgepole pine forests in British Columbia (BC) (Westfall & Ebata 2008) (Fig.1), the current beetle outbreak seems to be unprecedented in scale. As lodgepole pine comprises about one quarter of the provincial timber supply, socio-economic impacts of this beetle are enormous. A variety of management strategies can be used to reduce the effects of timber losses, the most important being salvage logging. In the short-term, adjusting harvest scheduling to remove standing beetle-killed trees can compensate some of the losses. However, due to market, operational, legal, and ecological constraints, the proportion of the beetle-killed forests that can be salvage-logged is limited.

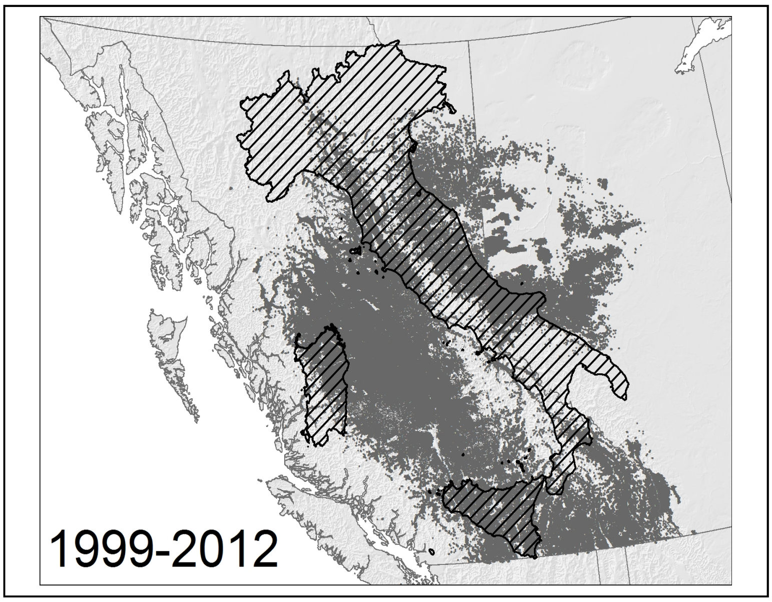

Figure 1: Map of British Columbia showing the extent of the mountain pine beetle infestation as of 2012. For size comparison, a map of Italy is shown in cross hatch.

Throughout much of British Columbia, lodgepole pine forms even-aged stands initiated by stand-replacing fires. Although such dynamics is considered typical for the species, uneven-aged lodgepole pine stands that have historically been maintained by frequent low-intensity surface fires are common in central BC. However, the disturbance ecology of these forests is changing. The frequency of fires has decreased over the last century, mostly due to effective fire suppression programs. When fire is infrequent, outbreaks of mountain pine beetle are likely to have a greater impact on forest structure, composition and dynamics. However, we know surprisingly little about the changes in forest characteristics following beetle outbreaks.

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The mountain pine beetle (Fig.2) generally has a one year cycle, usually attacking stands that are more than 80 years old, preferentially killing trees over 25 cm in diameter (Furniss & Carolin 1977) Safranyik et al 1974, Safranik 2004). Under epidemic conditions MPB preferentially kills the largest trees in the stand, and in large outbreaks, this results in the mortality of all or almost all of the mature trees within a given stand. The trees that are killed by mountain pine beetle turn red (around 2 years after initial attack), the needles fall off leaving a denuded tree which has a grey appearance (3 to 6 years). Dead trees eventually fall to the ground and become coarse woody debris. The removal of the tree foliage allows much more light to enter lower portions of the canopy, and trees that are not killed by beetle experience an accelerated period of growth (referred to as a growth release) which is enhanced by reduced competition.

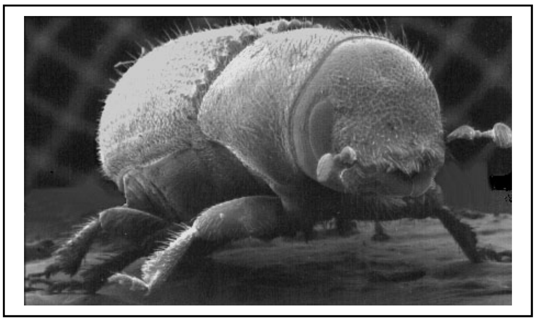

Figure 2: Scanning electron microscope picture of the mountain pine beetle. Real size about 4mm. Photo: Canadian Forest Service.

Tree rings maintain a record of the canopy disturbance history for a locality, and are useful indicators of ecosystem function. For this reason dendrochronology has been used to examine historical outbreaks of bark beetles (Heath and Alfaro 1989, Veblen et al. 1991, Axelson et al 2009). These studies utilize a release signal in tree rings from trees that survive outbreaks. This signal appears in the tree rings because during an outbreak not all trees in a forest stand are killed. Surviving trees take advantage of the mortality of the large trees in the canopy and accelerate their growth due to increased availability of light and nutrients. Thus, trees that survive show a period of accelerated growth or release in the rings as a result of canopy disturbance (Fig. 3).

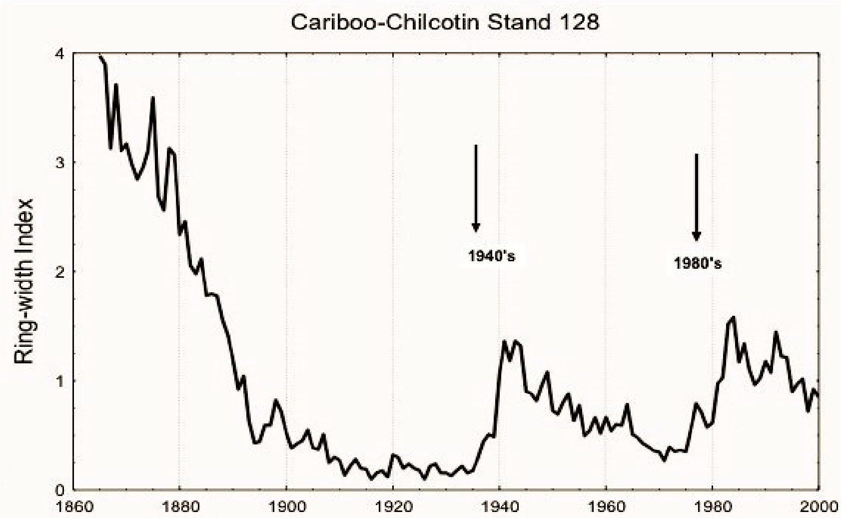

Figure 3: Chronology of trees that survived two mountain pine beetle outbreaks (1940's and 1980's) indicated by prolonged release periods.

Objectives

- To understand the current stand structure of even and uneven-aged lodgepole pine stands,
- To reconstruct stand dynamics following beetle outbreaks in even-aged and uneven-aged stands in the central interior of BC, and
- To characterize the disturbance regime by mountain pine beetle using Dendrochronology
- To develop conceptual models of stand dynamics that incorporate beetle and fire disturbances.

Methods

- We used forest inventory techniques to determine present stand structure of legacies after beetle by taking measurements such as: diameter at breast height, tree height, and mountain pine beetle attack status: no attack, green attack (current year), red attack (attacks occurred 2-3 years prior) or grey attack (attacks occurred more than 3 years ago).
- We used dendrochronology techniques to determine past stand structure by collecting tree increment cores and discs from dominant trees, saplings and dead downed trees (coarse woody debris). We then used tree-rings pattern matching and cross-dating to accurately date each ring in every sample to date past beetle episodes, past fire disturbances, year of tree establishment, and year of death.
- We used the tree-ring program JOLTS (Holmes 1999) to detect growth releases in individual trees, by computing a ratio of the forward and backward 10-year running means of ring-widths for each year. If this ratio exceeded 1.25 (i.e., a 25% increase in radial growth) for a given year, we counted a release for that year. The 10-year window has been found to sufficiently smooth ring-width variability due to short-term climatic variation (Berg et al. 2006). The ratio of 1.25 has been used in previous studies to document growth releases and effectively identifies periods of canopy thinning due to MPB outbreak (Alfaro et al. 2004; Taylor et al. 2006; Axelson et al. 2009).

Results

Fire history

Some wildfires and mountain pine beetle attacks leave permanent records in the form of scars on the tree bole. After careful dating of the tree-rings we identified the year in which a fire or mountain pine beetle attacks occurred. Based on tree-ring dating we found that in even-aged stands forests were initiated by a stand replacing event (crown fires) in the late 1800s or the early 1900s. In the uneven-aged stands we found that many less severe fires occurred, leaving multiple scars on surviving trees but not necessarily eliminating the entire stand.

Mountain pine beetle outbreaks history

Since the late 1800's residual trees in both even and uneven-aged stands experienced a sustained increases in annual growth during the 1930s, 1960s and the 1980s (Fig. 4), which all coincide with known periods of beetle outbreak in British Columbia, as recorded by the Forest Insect and Disease Survey of the Canadian Forest Service. We could not determine the history of beetle for previous centuries because lodgepole pine is a short lived species, with the sampled trees having originated following stand replacing fire disturbance in the late 1800's.

Based on 80 stands sampled throughout the central portion of British Columbia we determined that the averaged beetle return interval was approximately 40 years (Table 1).

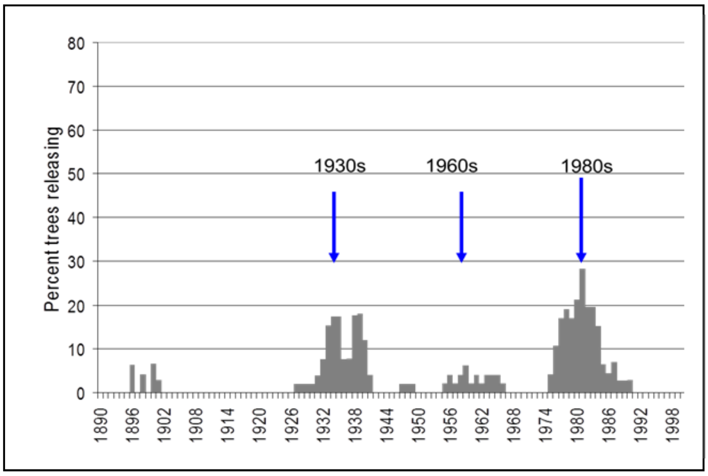

Figure 4: Periods of release in tree rings from stands affected by three mountain pine beetle outbreaks (1930's, 1960's and 1980's)

Table 1. Duration of growth release in tree rings and mean beetle return interval, in 80 lodgepole stands in British Columbia. Growth release is a proxy variable that indicates canopy removal by mountain pine beetle.

Province	No of stands sampled	Average first year of chronology	Mean release duration years	Mean beetle return interval - years
British Columbia	80	1876	8	40.2

Forests Today

Forest structure

Examination of the diameter at breast height (DBH) and height distributions of the sample stands revealed the prevalence of different forest layers, or cohorts, in both the even- and uneven-aged forests. In the even-aged stands the largest and oldest trees were very large Douglas-fir trees, or veterans, which survived stand replacing fires in the late 1800s and early 1900s. The dominant canopy, which initiated after stand replacing fires, contained the oldest pine in the stand. Below this layer was a lodgepole pine dominated sub-canopy, which was initiated after the 1930s beetle outbreak thinned the dominant canopy. The advanced regeneration dated to the 1980s and was initiated after the 1980s outbreak. Some seedlings were present, initiating around 2004-2005, but they were very infrequent due to very low light conditions at the forest floor.

In the uneven-aged stands there were no Douglas-fir veterans present, and so the oldest trees in the dominant canopy were lodgepole pines. Because of the mixed-severity fire regime of this area, many pine trees survived ground fires and, as a result did not establish in one single pulse (as in the even-aged stand). Also present in the dominant canopy were trembling aspen, which likely established after ground fire events. The next layer was the sub-canopy which contained both pine and aspen which were both largely initiated after beetle outbreaks of the 1930s and 1960s. Similar to the even-aged stands the advanced regeneration layer dates to the 1980s and was initiated after the 1980s outbreak. Unlike the even-aged stands numerous seedlings were present, initiating around 2004-2005, as there was ample light in these stands due to the open canopy with few live mature pine trees.

Stand development after beetle

Mountain pine beetle is a natural thinning agent that promotes increased growth among the surviving trees and allows for establishment of seedlings in understory. In all sampled stands the sub-canopy, which consisted of a well-developed cohort in both even and uneven-aged stands, was mainly free of mountain pine beetle attack and will endure after the dominant-canopy which has been killed by MPB has fallen to the ground. The advanced regeneration layer was present and along with the sub-canopy forms an important secondary structure, meaning that the entire forest was not all dead.

Putting it all Together

Forest disturbances such as wildfire and mountain pine beetle outbreaks are natural processes that operate on the stand to landscape level. We were able to develop a conceptual model of stand dynamics in lodgepole pine ecosystems in BC (Axelson *et al* 2009, 2010). This model shows that in the absence of fire mountain pine beetle plays a more important and frequent role in determining forest structure and species composition in both the southern and central interior regions of British Columbia.

Conclusion

- In the absence of fire disturbance the MPB plays a more frequent role in directing stand dynamics and structure in the lodgepole pine stands of BC.
- Stand replacing fires initiate even-aged lodgepole pine stands; multiple MPB disturbances create stands that have variable canopy and cohort structure.
- Mixed severity fires create complex structures in uneven-aged lodgepole pine stands; multiple MPB disturbances maintain complex stand structures and contributes towards the succession of non-pine tree species (e.g., trembling aspen).
- Frequency and severity of MPB outbreaks determines the structure and composition of the residual stand.

Acknowledgements

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Hydroclimatic effects on the condition of grey alder (*Alnus incana* L. Moench) and European larch (*Larix decidua* L. Mill.) growing in the riparian forest of an incised mountain river

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Introduction

Vertical stability of river channels is a key control on the condition of riparian vegetation communities, including riparian forests. It determines the frequency of inundation of riparian areas (Dufour, Piégay, 2008), and thus the thickness and fertility of soil, as well as the availability of water for root plants. Widespread human impact on river channels in the 20th century has resulted in a common occurrence of river incision (Wyżga, 2008). This phenomenon enlarges the flow capacity of the channel and increases the elevation of floodplain areas over the water level in the river, that may worsen the condition of riparian forest (Dufour, Piégay, 2008) or even lead to its decline (Stella et al., 2013).
The influence of river incision on the condition of riparian forest can be readily demonstrated in the neighbouring incised and vertically stable river reaches. Such variation in the vertical tendencies of channel bed can be observed in the Czarny Dunajec, the upper course of the second largest river of the Polish Carpathians (Zawiejska, Wyżga, 2010). The study was carried out in the middle course of the Czarny Dunajec, in which a wide and shallow, multi-thread channel had existed until the mid-1970s (Fig. 1).

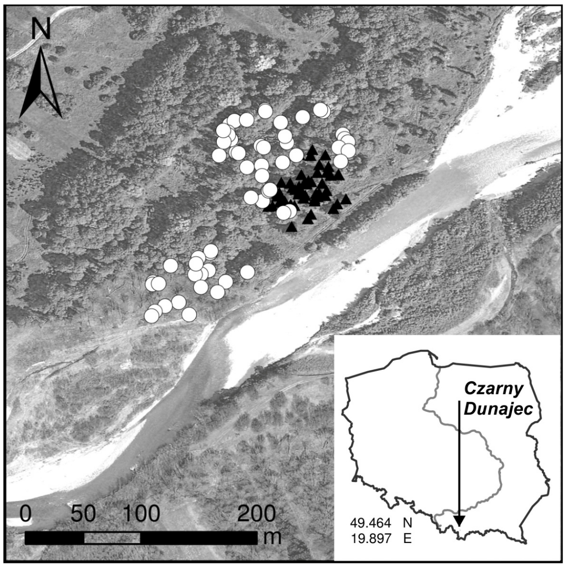

Figure 1: Location of the study site in the foothills of the Tatra Mountains in southern Poland and detailed location of 87 investigated trees on the riverbank of the Czarny Dunajec: alder (white circles) and larch (black triangles).

Along a portion of this reach, the river has remained unmanaged, maintaining the multi-thread channel pattern and vertical stability of its bed. Here, width of the active zone of the river currently exceeds 150 m and the banks are 0.7-1.2 m in height. In the lower portion of the reach, the river was channelized in the years 1974-1976, with the former multi-thread channel replaced by an artificially formed, single-thread channel about 40 m wide. The bed of the regulated channel was positioned about 1 m lower than the bed of the former, natural channel. In response to the increase in transport capacity of the river caused by its considerable narrowing and the concentration of flow in the single channel (Wyżga, 1993, 2008), the bed degraded by further 0.5 m as indicated by a comparison of its elevation in the constructed regulated channel with its current position. A complete lack of the cover of fine-grained, overbank deposits on the gravel bank formed in the course of the river channelization shows that channel incision must have been rapid, lasting only a few years at most. As a result of the mentioned changes, the riparian forest adjacent to the regulated channel ceased to be inundated by flood flows and the height of the river banks increased to 2.4-2.6 m (Fig. 2). The environmental changes were accompanied by modifications of the riparian forest. The systematic tree logging and introduction of a tree species typical of other habitats are two main factors that have influenced the character of the investigated forest.

The aim of this study was to assess the influence of climatic and hydrological factors on two tree species of different origin, which now grow together in the riparian zone of the incised river. Grey alder (*Alnus incana* L. Moench) represents a native species typical of the mineral *Alnetum incanae* riverside forest and is a light-demanding and fast-growing broadleaf tree that prefers moist soil. Alders are actinorhizal trees capable to fix atmospheric dinitrogen due to the symbiosis with actinomycetes (Furlow, 1979). European larch (*Larix decidua* L. Mill.) was introduced in the riparian forest for economical reasons as a good source of timber. The larch is also a light-demanding and fast-growing species but it prefers well-drained soil.

Figure 2: A section of the Czarny Dunajec River channelized in the mid-1970s (photo taken in 2012). The single-thread channel, about 40 m wide and with banks 2.4-2.6 m in height, is the result of the channelization and subsequent channel incision. The investigated riparian forest consists of the introduced European larch (higher trees) and grey alder typical of the riparian habitat.

Materials and methods

The study site was selected according to the results of cartographic analyses and field inspection of the Czarny Dunajec River. The chosen sampling site represents typical channel and riparian zone of the formerly braided mountain river that was modified by channelization. The samples were collected using a standard increment borer at standard height (BH = 1.3m). The cores from 56 larches (LADE) and 60 alders (ALIN) were taken. The cores were prepared for the measurement of ring width using CDendro 7.7 system (Cybis Elektronik & Data AB company). The final preparation of the cores differed between the two species. Larch cores were polished with 500 grid sand paper, whereas much finer (up to 1200 grid) sand paper had to be used to achieve a clear image of the rings of alder. Also acquisition of digital pictures was adjusted to meet the demands of diffuse-porous wood samples of alder. They were scanned with resolution ranging from 2400 to 4800 DPI, whereas 1200-2400 DPI was sufficient to obtain good-quality images of larch samples. The ring width was measured using CooRecorder 7.7 (Cybis Elektronik & Data AB company) software based on digital pictures of cores. Visual examination of actual cores, under a binocular, clarified the doubtful features of digital images. The quality of tree ring width (TRW) series was assessed with Cofecha software (Holmes 1983, Grissino-Mayer 2001). The final cross-dating and the selection of series used for further analyses was performed based on the visual inspection of TRW graphs and occasionally also re-examination of samples. These tree-ring series were detrended to remove the age-related trend and residual chronologies were built using Arstan software (Cook 1985). The cubic smoothing splines with a 50% frequency-response cut off at 200 years were employed and their variance was stabilized over time (Cook, Peters 1997). The main hydrological and climatic factors affecting the growth of the tree species were identified on the basis of correlation analysis between residual chronologies and six series of the following parameters: i) mean temperature, ii) precipitation, iii) monthly PDSI, iv) minimal discharge, v) mean discharge, vi) maximum discharge (all monthly values). Here we present only statistically significant results. The gridded climatic data (CRU TS 3.10) (Jones, Harris 2013) and hydrological data from the Koniówka gauge station located 7 km upstream from the sampling site were used in the analysis.

Results

Both the maximum and average age of sampled trees is similar for the two investigated species. For alder it amounts to 49 and 40 years, respectively, while to 46 and 40 years for larch. After statistical and visual examination of 60 sampled alder trees, 48 were selected to create chronology. Similarly, from the sample of 56 larch trees, 41 were included in the set to compute coherent chronology. The alder showed a slightly lower average growth rate than larch (2.92 and 3.33 mm respectively). Accidentally, the two analysed chronologies reached the threshold of minimum replication of five samples in 1967 (fig. 3).

The raw chronologies showed a similar pattern, revealing strong temporal trend. The main differences are visible in the 1970s and at the end of the 2000s. The first period is that of the channel regulation. Alder showed a decrease in tree-ring widths over several consecutive years, whereas larch did not show a clear reaction. In the last years the two chronologies are out of phase. The main reason is different reaction of alder and larch to the spring flood in 2010. The common minimum of growth was registered in 1987 and 1996.

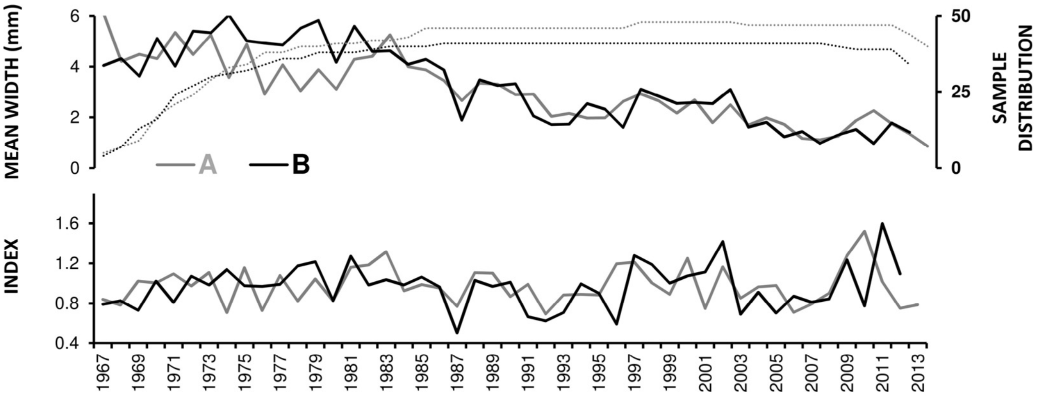

Figure 3: Raw (upper diagram) and residual (lower diagram) chronology of grey alder (A) and European larch (B) for the common period of 1967–2013. The sample distribution is displayed as a dotted line in respective colour.

We computed correlation between residual chronologies and monthly (from January to October), seasonal and annual averages of climatic and hydrological data (Fig. 4). Additionally, to determine the autocorrelation, the similar calculation was done for chronologies lagged by 0, +1 to +5 years (Fig. 5).

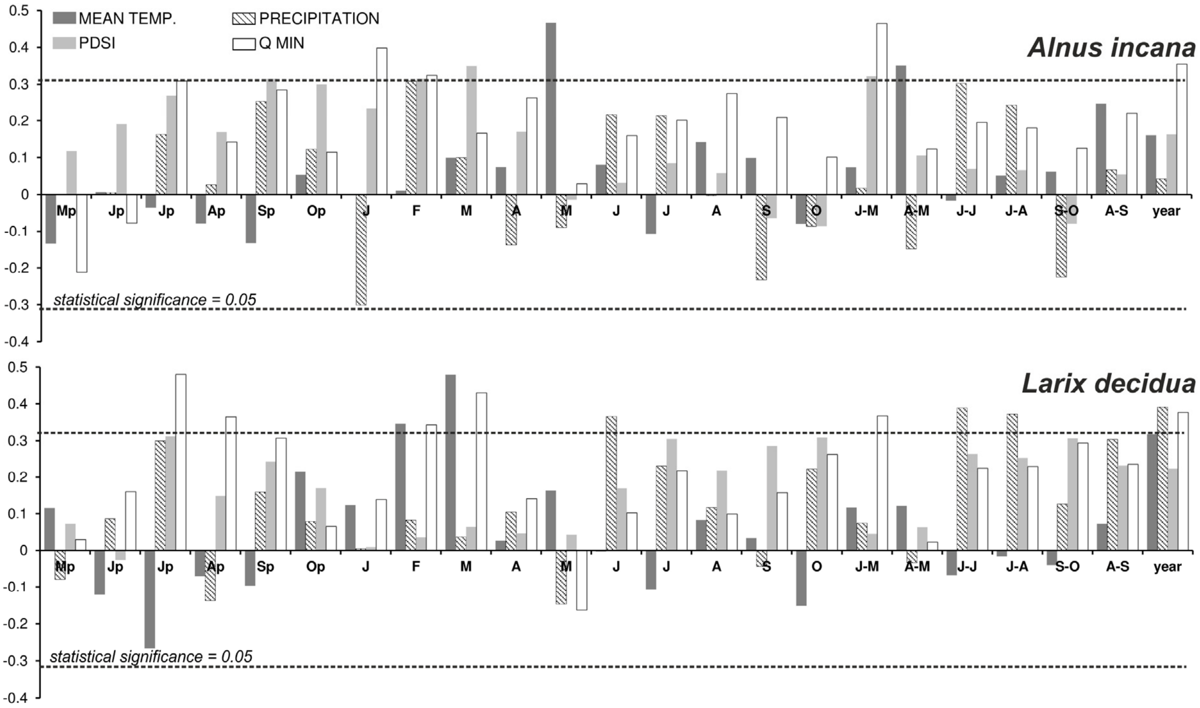

Figure 4: TRW response to mean monthly temperature, precipitation, PDSI and minimal monthly discharge calculated for the period 1973–2009.

The correlation analyses reveal the hydroclimatic controls exerted on both species. The highest correlation (r=0.49) was derived between larch chronology and the minimum discharge in March of the previous year (lag+1). The similarly high correlation was obtained between TRW and the temperature in March of a given year (lag=0). The growth rates show a significant ($p < 0.05$) response to hydroclimatic conditions during summer (July and August) of the previous year. The amount of available water, regardless of its source (river-derived groundwater or rain), controls the larch growth in the next year. The high correlation between TRW and water discharge in February and March extends this important period to several months before a growing season. During the vegetation period, tree growth depends more on precipitation (June, June-July, June-August) than on the discharge in the adjacent river. The analyses of autocorrelation reveal strong carryover effect. The correlation between TRW and lag+2 February discharge was one of the highest obtained from the analyses (r=0.49). The alder TRW chronology correlates strongly with the temperature in May (r=0.47) and the discharge during January-March of a given year (r=0.46). The availability of river-derived groundwater seems to be more important for this species, whereas no significant correlations with precipitation in all analysed periods were obtained. The growth of alder is driven by groundwater during end of winter and beginning of spring (January-March) and also by spring (April-May) temperature.

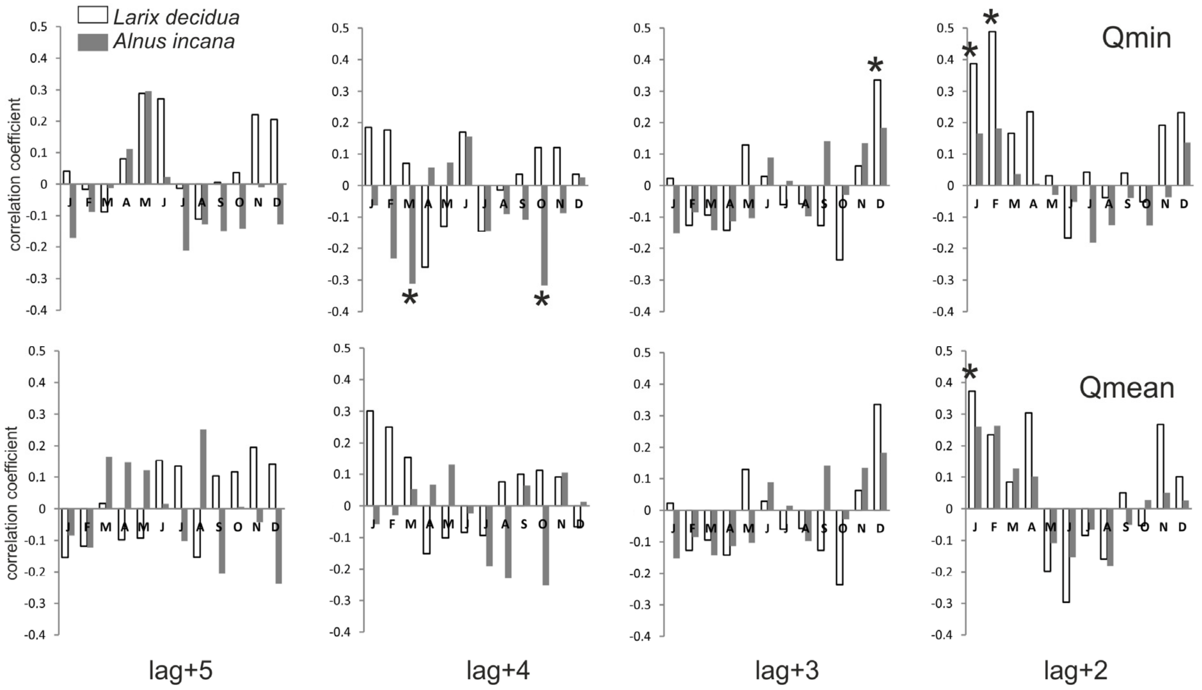

Figure 5: TRW response to mean and minimal monthly discharge calculated for the period 1973–2009. The stars indicate the results significant at level p=0.05.

This species also showed a statistically significant correlation with spring drought, expressed by PSDI index (Palmer Drought Severity Index) (Palmer 1965). Similar relation to available groundwater was observed for other riparian species (Mahoney, Rood 1991, Vreugdenhil et al. 2006). The soil moisture is important for the actinomycetes living in symbiosis with alder and responsible for fixing atmospheric nitrogen (Kaelke, Dawson 2003). Alder is also less dependent on the conditions in the previous year. Only winter discharge (last December-February) showed a significant influence on TRW. The analyses of autocorrelation derived also a correlation of -0.30 between TRW and lag+4 March and October discharge. The results of the analyses helped to understand the mechanisms responsible for the development of particularly narrow rings in 1987 and 1996. Short growth depressions are common for alder and larch. 1987 was one of the coldest years in the analysed period, and the water discharge in 1986 was significantly below the average. In 1996 the summer was also colder than usually but during that and the previous years, the river discharge was near to average. These hydroclimatic conditions resulted in a narrow ring of larch and an average one of alder.

Conclusions

The river channelization performed in the years 1974–1976 and the resultant channel incision have significantly changed the conditions for riparian forest growth. The channel regulation caused both immediate and subsequent changes of the valley-floor environment. The age of the trees of both examined species does not allow to assess these changes by a simple comparison of pre- and post-regulation periods. Therefore, further studies focused on control (natural) sites are needed. The growth of larch and alder is driven by climate and hydrological conditions of the riparian zone. The relation between tree growth and hydroclimatic conditions is complex. It was difficult to identify the main factor controlling growth of these species as both temperature and soil moisture (related to precipitation and high river discharge) are equally important for their vitality. Alder, the species typical of riparian habitat, and larch, introduced by man, react positively to warm spring and negatively to dry periods. Further channel incision and climate warming will have a negative influence on the conditions of the riparian forest. Alder trees, more sensitive to drought, may not survive. The larch, also sensitive to the lack of soil moisture, is not a good substitute for them.

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Growth effects of thinning operation in an umbrella pine (*Pinus pinea* L.) stand in central Italy

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Introduction

Intermediate cut is a practice during the period between seeding and maturity. It is done to improve the existing stand and regulate its growth without any effort directed at regeneration.

The main goals are enhancing ecosystem functioning and species diversity, increasing individual tree diameter, reducing water loss caused by interception of rainfall specially in environments more susceptible to drought, increasing net primary production, saving management costs, and mitigation of the effects of drought in the Mediterranean basin due to the climatic change (De las Heras et al. 2013, Mazza at al. 2011, Pasho et al. 2012, Seiwa et al. 2012).

In Italy currently the timber from first thinning in broadleaf stands has a developed firewood market (Lo Monaco et al. 2011, Picchio et al. 2011b), nevertheless in coniferous forests the thinning produces unappreciated materials, but with ascertained good energetic characteristics for fuelwood (Picchio et al. 2012c). Mechanized harvesting techniques have been increasingly improved productivity and reduced logging costs (Picchio et al. 2011b, Maesano et al. 2013). During thinning operations, logging injury to the remaining trees may lead to serious economic losses of timber quality at the final harvest. Behjou (2012) found a 39% loss of log values losses of damaged trees and tree growth reduction (Behjou & Mollabashi 2011, Vasiliauskas, 2001). The level of damage in residual trees, seedlings and timber products was significantly affected by the timber harvesting techniques. In spruce forests Eroglu et al. (2009) found in Turkey that the higher mechanization level is adopted lower are the damages to residual stand. Although equal stand conditions may often be difficult to replicate, Granhus & Fjeld (2009) have reached opposite conclusions, in multistoried spruce stands in southeast Norway. On the Mediterranean area few studies have been concerned with damage to remaining trees. Some studies have taken into account both coppiced and high forests, species and sites characteristics, different forestry treatment as well as machines and work methods which may have different impacts on the trees and on forest soil (Spinelli et al. 2010, Picchio et al. 2011a, 2012a, 2012b, Tsioras & Liamas 2011, Magagnotti et al. 2012, Pinard & Putz 1996). Kiser (2011) and Ezzati & Najafi (2009) observed that wounds inflicted during thinning operations deteriorate the timber quality and stated a loss of volume and value of timber. Nevertheless the interesting issue, few authors have studied the relationship between the damage and the radial growth. Picchio et al. (2011a) reported that no difference was recorded in growth between damaged and undamaged trees of Pinus laricio Poiret planted on hill of central Italy, in moist temperate climate. Umbrella pine (*Pinus pinea* L.) is one of the most important Italian Mediterranean pine. It has been cultivated traditionally for the production of both wood and pine nuts. On the Tyrrhenian coastline these plantations have assumed higher recreational and landscape value. This study aimed to evaluate the impact of thinning and the wound influence in terms of ring growth on the remaining trees 11 years after the operation in a typical Mediterranean pine plantation.

Materials and methods

During the winter 2000-2001 a first thinning was carried out in an Umbrella pine plantation, located at Riotorto in the municipality of Piombino (LI), Central Italy (Fig. 1). The thinning was

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predominantly geometric, cutting a row every two, and selective on the row. The geometric scheme was not always met due to the presence of dead, unhealthy or poorly shaped trees.

Figure 1: The study area localization

For this reason the results were not uniform and different thinning intensities were observed. Based on the dendrometric data, detected during the survey in spring 2012, the area was divided into two particles due to the different tree density. Each particles was divided in two macro-plots characterized by different tree diameter at breast high (DBH) (Fig.2).

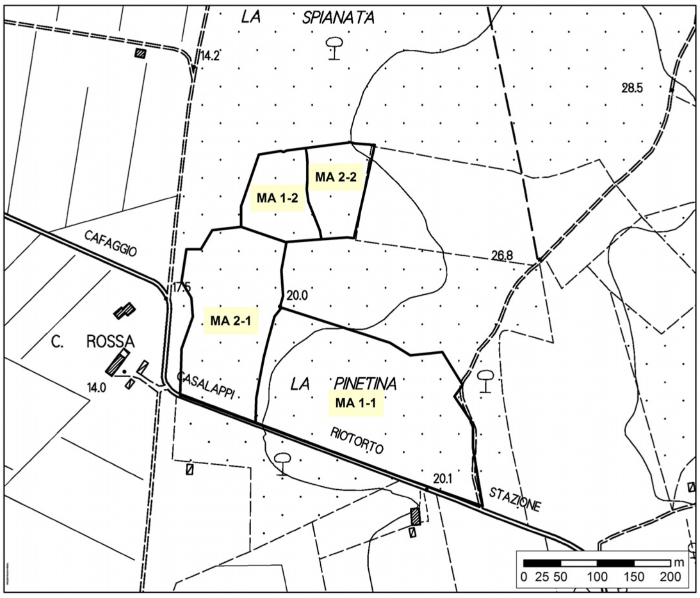

Figure 2: The particles and the macro-plots (MA1-1 and MA2-1 particle 1; MA1-2 and MA2-2 particle 2)

The macro-plots were subjected to different thinning intensity, ranged from 30 to 60 % of basal area removed. Logging operations were carried out with a semi-mechanized logging systems: felling was performed by chainsaw, extraction was by skidding with a tracked agricultural tractor driving in the inter-rows. The short wood system was applied.

Damages to standing trees were investigated in the thinned macro-plots in 2012. The following parameters were recorded (Concerted Action N° AIR3-CT94-2097, 1997): number of damaged trees, DBH; crown class, i.e. dominant, co-dominant, and dominated; type of damaged tissues, i.e.

bark, bast, wood fibres; cause of damage, i.e. felling or bunching/skidding; location of wounds; size of wounds. Trees damaged in several parts were classified on the basis of the most severe damage. The agent of damage (felling, skidding) was inferred on the basis of the position and size of the wound, following Picchio et al. (2011a).

Stem cores were collected at breast height, both in damaged and undamaged trees to evaluate the effect of thinning and injuries on radial growth. Ring width were measured and recorded by CATRAS (Aniol 1983).

Factorial ANOVA was applied to the ring widths, considering the growth year, the status of damage, and the combination of these, restricted to the last eleven years after the thinning. A t test for independent samples was applied to check differences between average ring width of the eleven years before and after the thinning, to check differences between average ring width of the eleven years before and after the thinning.

Results

In spring 2012 the survey showed different density in term of tree/ha and different average DBH (Tab. 1).

Table 1: The main dendrometric parameters of thinning

Macro Plot	*Before thinning*			*After thinning*			*11 years after thinning*		
	trees (n/ha)	*DBH (cm)*	*Basal area (m^2/ha)*	*trees (n/ha)*	*DBH (cm)*	*Basal area (m^2/ha)*	*DBH (cm)*	*Basal area (m^2/ha)*	*Thinning intensity (%)*
MA1-1	*535*	*19.0±2.1*	*15.2*	*214*	*22.2±1.9*	*8.3*	*34.8±2.2*	*20.3*	*45*
MA2-1	*513*	*19.2±1.9*	*14.8*	*154*	*28.6±2.1*	*9.9*	*38.3±2.0*	*17.7*	*33*
MA1-2	*990*	*16.0±4.1*	*19.9*	*276*	*22.8±1.1*	*11.3*	*31.0±1.2*	*20.8*	*43*
MA2-2	*1109*	*17.1±2.8*	*25.5*	*276*	*20.0±3.1*	*10.5*	*27.5±1.8*	*19.8*	*59*

Mortality after thinning was 6% and no statistical difference was recorded among the macro-plots. Damage frequency ranged from 9 to 14 % and wound severity was related with the higher frequency of wound occurrence (Tab. 2).

Table 2: Damage frequency and severity

Macro-plot	*Damaged trees n./ha*	*Damaged trees %*	*Seriously wounded trees %*
MA1-1	*30*	*14*	*61*
MA2-1	*18*	*12*	*46*
MA1-2	*25*	*9*	*33*
MA2-2	*33*	*10*	*33*

The main cause of the injuries inflicted to the trees, was due to felling operations, mostly in the plots with high trees density. The passage of tractor follows as cause of damage located at the base of the trees. The short wood system applied, although inappropriate to the type of intervention, is deeply ingrained in the practices of local workers, as common in Italy.

In order of evaluating the effect of injuries on radial growth, factorial ANOVA and t test were applied. In Parcel 1, on both macro plot 1 and 2, factorial ANOVA (Tab. 3) shows significant differences in "year" and "tree status", but not in the combination of these, in the last eleven years after the thinning.

Table 3: The effect of injuries on radial growth on parcell 1

	Macro-plot MA1-1			Macro-plot MA2-1		
Variable	Ring (n.)	fd	p-value	Ring (n.)	fd	p-value
Year	220	10	<0.01	220	10	<0.01
Trees status		1	<0.01		1	<0.05
Year x Trees status		10	>0.05		10	>0.05

In Parcel 2, factorial ANOVA (Tab. 4) shows significant differences only in "year" for macro plot MA1-2, but not in "tree status" and in the combination of these, in the last eleven years after the thinning. In macro plot MA2-2 there are no significant differences for each variables.

Table 4: The effect of injuries on radial growth on parcell 2

	Macro-plot MA1-2			Macro-plot MA2-2		
Variable	Ring (n.)	fd	p-value	Ring (n.)	fd	p-value
Year	43	10	<0.05	36	10	>0.05
Trees status		1	>0.05		1	>0.05
Year x Trees status		10	>0.05		6	>0.05

However the t test shows a significant increase of the average radial growth after the thinning in the parcel 1 - macro-plot 1 (MA1-1) and 2 (MA2-1) - (Tab. 5), and in the parcel 2 only in macro plot 2 (MA2-2) (Tab. 6). In macro plot 1 (MA1-2) of the parcel 2 (Tab.6) no-significant increase of average radial growth was observed.

Table 5: Parcel 1: t test on ring growth widths before and after the thinning in damaged trees

Macro-plot	Average growth after thinning	Average growth before thinning	fd	p-value	Rings number after thinning	Rings number before thinning
MA1-1	2.35	1.86	438	<0.01	220	220
MA2-1	2.5	2.28	482	<0.05	242	242

Table 6: Parcel 2: t test on ring growth widths before and after the thinning in damaged trees

Macro-plot	Average growth after thinning	Average growth before thinning	fd	p-value	Rings number after thinning	Rings number before thinning
MA1-2	2.51	3.04	64	>0.05	33	33
MA2-2	1.67	2.85	42	<0.05	22	22

Thus, significant differences in radial growth between damaged and no-damaged trees were not recorded. In order to better understand the effect of the thinning, the intensity was expressed as a percentage decrease of basal area due to the thinning (Tab.7). It is in some way proportional to the percentage increase of the annual growth. At lower intensity of thinning, the radial growth decreases, while at higher intensity the DBH is significantly lower.

*Table 7: Thinning intensity and growth recovery expressed as basal area. *Note: only in this case, the t test shows a no-significant increase of the average radial growth after the thinning in parcel 2 macro-plot 1.*

Macro-plot	*Increased growth after thinning (%)*	*Thinning intensity (%)*
MA1-1	*28*	*45*
MA2-1	*9*	*33*
*MA1-2**	*20*	*43*
MA2-2	*64*	*59*

The recovery in basal area was higher in the intensive thinned macroplots. The average DBH was higher in weakly thinned areas compared to the intensively thinned ones. The recovery of the total basal area in the macro plots indicates that the thinning intensity, which seems to provide the best results in terms of mass and stability of the stand, is around 45%.

Discussion

In 2012 differences in the main dendrometric parameters were found in the parcels and in the macro-plots and correspond in part to those that were found immediately after the thinning. After thinning the average DBH and height in the macro-plots increased and basal area decreased, as effect of thinning (Roberts and Harrington, 2008), due to the different number of stems and the cutting of the smaller diameter trees (Mäkinen and Isomäki, 2004).

The wounds were due to the felling operations and harvesting system (SWS). Similar results were observed by Magagnotti et al. (2012) reporting 5 % of wounded trees in a 35 year old pine stand removing 36% of trees, but the whole tree system were applied. Spinelli et al. (2010) and Picchio et al. (2011a) found damages to the 14 % of residual pine trees, but in pine plantations much more fertile, with basal area also double of that found in this study. Total injury (injured + dead) to saplings in a multistoried spruce stands in southeast Norway were observed to vary from 17 to 76% and with a mortality varying from 5 to 51% (Granhus and Fjeld, 2001). Tsioras & Liamas, 2010 in a mixed beech and oak stand observed that one fifth (19.7%) of the monitored trees were damaged. Eroglu et al. (2009) studied the impacts of timber harvesting techniques (manpower, skidder, and skyline) on residual trees, seedlings, and timber products in natural oriental spruce stands in Turkey. The degree of damage was significantly affected by the timber harvesting techniques, with more than 80% of the residual trees damaged by manpower and skidder harvesting techniques, but less than 35% of the residual trees by skyline method. Athanassiadis (1997) recorded residual stand damage during harvesting operations using a farm tractor in two conifer stands. Damaged tree percentage was up to 6.5%.

Behjou et al. (2012) highlighted that logging system and slope gradient had a significant impact on damages.

Growth effects of thinning injuries were not recorded, as noted in a Corsican pine (Pinus laricio Poiret) stand in central Italy (Picchio et al. 2011a).

The effect of the thinning, assessed as basal area, was reveled by the DBH that was higher in weakly thinned areas compared to the intensively thinned ones. Seiwa et al. (2012) obtained similar results in a Cryptomeria japonica plantation managed with different thinning intensity (33% weak thinned treatment, and 67% intensive thinned treatments).

Conclusions

- This study confirms the effect of thinning on growth rate for the considered period, although significant differences in radial growth between damaged and no-damaged trees were not recorded. However the quality of the final harvest will not be uniform.
- In addition, the macro-plot 2- parcel 1 (MA2-1) thinned with lower intensity, just eleven years after, the incremental effects are very low (about 9%). The macro-plot 1- parcel 2 (MA1-2) thinned with medium intensity, just eleven years after, the incremental effects are no statistically significant, compared to the previous period, in terms of average radial growth, due to the thinning that in this plot has released mainly dominant trees. In the macro-plot 2- parcel 2 (MA2-2) thinned with high intensity, just eleven years after, the incremental effects are statistically significant and they are very high (about 65%), compared to the previous period, in terms of average radial growth, due to the thinning that in this plot has released mainly co-dominant and rarely dominated trees. This is also the only case in which the average basal area did not reach the “before thinning” value.
- The percentage increase of the annual growth is in some way proportional to the thinning intensity.
- The recovery of the total basal area in the macro plots MA1-1, MA2-1 and MA1-2 indicates that the thinning intensity, which seems to provide the best results in terms of mass and stability of the stand, is around 45% of basal area. At lower intensity of thinning, the radial growth decreases, while at higher intensity the DBH is significantly lower.
- To limit damages on the remaining trees and to increase the positive thinning effect on the trees growth it is important a correct intervention planning supported by an appropriate logging system.
- Better understanding the effects of silvicultural operations can direct the management to a different intervention planning to limit damage to the remaining trees. Analyzing the injuries to the trees, management can judge whether and to what degree the actions undertaken have achieved the design expectations.

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Possibility to distinguish tree-ring reductions caused by landsliding and by air pollution
(example from Western Carpathians)

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Introduction

Tree-ring reductions occur in trees due to the impact of diverse environmental factors e.g. air pollution, insect outbreaks, stem wounding etc. (Thompson 1981, Camarero et al. 2003, Danek 2007, Malik & Owczarek 2009). Multiple factors causing reductions can act at the same time in the same area (Ashby & Fritts 1972), so environmental reconstructions can be affected by errors. Therefore there is a need to conduct studies on recognizing specific environmental factors responsible for tree-ring reductions. In the Polish Carpathians we have studied European silver fir (*Abies alba* Mill.) specimens growing on landslide slopes and at the same time within the zone affected by air pollution. Preliminary studies have shown that these trees develop strongly reduced annual rings. The aim of the research was to develop a basis for distinguishing tree-ring reductions caused by landsliding from reductions caused by air pollution.

Study area

The study was carried out on a slope of the Kamień Mt (857 m a.s.l.), in Beskid Niski (Western Carpathians, Poland, Fig. 1). We have selected two sampling sites: the first located on a landslide slope, the second one a stable reference site, 1 km from the landslide slope. Bedrock of the Beskid Niski Mts. is composed of flysch sandstones and shales which create favourable conditions for landslide development. Earlier studies have shown a high frequency of small-scale landslide movements occurring almost every year in the Carpathians (Wistuba et al. 2013). Climate conditions in the study area are typical for lower mountain ranges of the Carpathians with precipitation of ca. 800 mm per year. The study area is located in Magura National Park with natural beech and fir forests. There are no large urban and industrial areas in less than 20 km from Kamień Mt, but the study area is located within an old Central Industrial District (CID) which flourished in Poland from 1920 to 1940. Steel mills, chemical and power plants, automobile and aircraft factories were developed in the CID. After the 2nd World War CID began to decline but other industrial districts developed and emitted harmful air pollution to the atmosphere from 1960 to 1990 (Malik et al., 2012). After 1990 environmentally friendly technologies were introduced and air pollution decreasedand the suppression of tree growth stopped.

Methods

In Kamień massif we have sampled 20 silver fir specimens. Using Pressler borer we took two cores from each tree, first from the upslope side of each stem and the second from the downslope side. Half of the sampled trees were growing on the landslide slope, the other half on the stable reference slope (without any growth disturbances caused by landsliding). For all trees ring-width measurements were done and chronologies for the landslide slope and the reference site were developed separately.

We also calculated ring reductions and divided them into three classes (Schweingruber et al. 1985):

1) moderate reductions: 30-50%,
2) strong reductions: 50-70%,
3) very strong reductions: >70%.

Furthermore, the percentage of sampled trees showing ring reductions in each year was calculated. These ring reductions were also devided into three groups:

1) reductions formed only on one side of a stem,
2) reductions formed on both sides of a stem with the same depth,
3) reductions formed on both sides of a stem with different depth.

We presumed that reductions formed only on one side of a stem are caused by landsliding, because trees growing on an active landslide are tilted and produce eccentric rings (Braam 1987), reduced on one side of the stem only (up- or downslope). On the other hand trees affected by air pollution produce reduced rings within the whole stem perimeter. Trees affected simultaneously by landsliding and air pollution produce reduced rings within the whole stem perimeter, but with different depth of reduction on up- and downslope side of a stem.

We have also calculated the number of missing rings within all samples taken and used them as a record of environmental stress affecting trees.

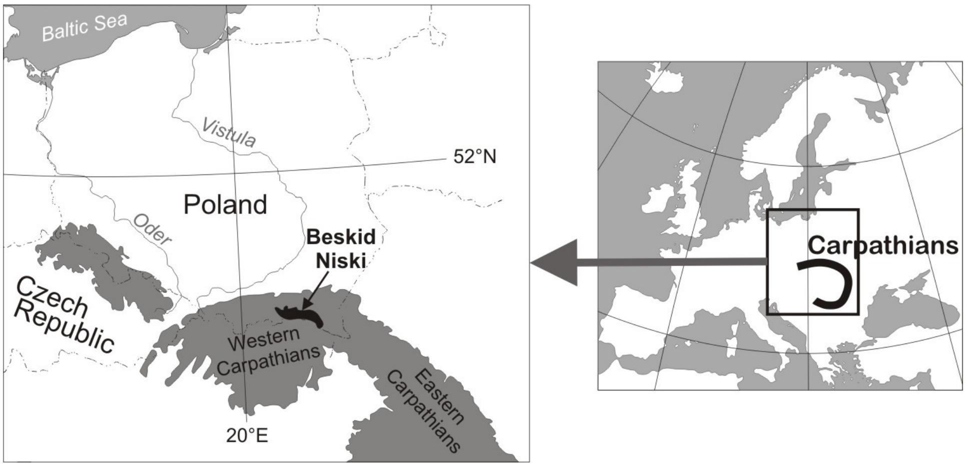

Figure 1: Study area.

Results and Discussion

Based on the chronologies developed for both sites, we have found periods with tree-growth suppressions (Fig. 2). In the chronology developed from trees growing on the landslide slope, strong reductions occur in 1920-1950 (Fig. 2A). The period is synchronous with the development and prosperity of the Central Industrial District, which means that tree-ring reductions probably were caused by the appearance of industrial air pollution, but we can't also exclude landslading as a factor that determined reductions.

In the chronology developed from annual rings of trees growing on a reference slope reductions occur in 1960-1995, chronology is relatively short, and it id not possible to This period is characterized by the dynamic development of industry not only in Poland but also in whole Europe. Numerous examples of ring suppressions due to air pollution are known from this period, even from areas located relatively far from sources of pollution (Juknys et al. 2003, Elling et al. 2009). We suppose that reductions in the studied firs in 1960-1990 also result from air pollution. By comparing both chronologies we have found that in the period 1960-1995 trees growing on the reference site have developed clearly stronger reductions than trees growing on the landslide slope (Fig. 2A). It is probably an effect of eccentric growth of trees on active landslide slopes.

Reductions on one side of a stem are accompanied by more intensive growth and wider rings on the opposite side of the stem. The situation is typical for trees growing in tilted position due to different environmental factors, among them landsliding (Wistuba et al. 2013).

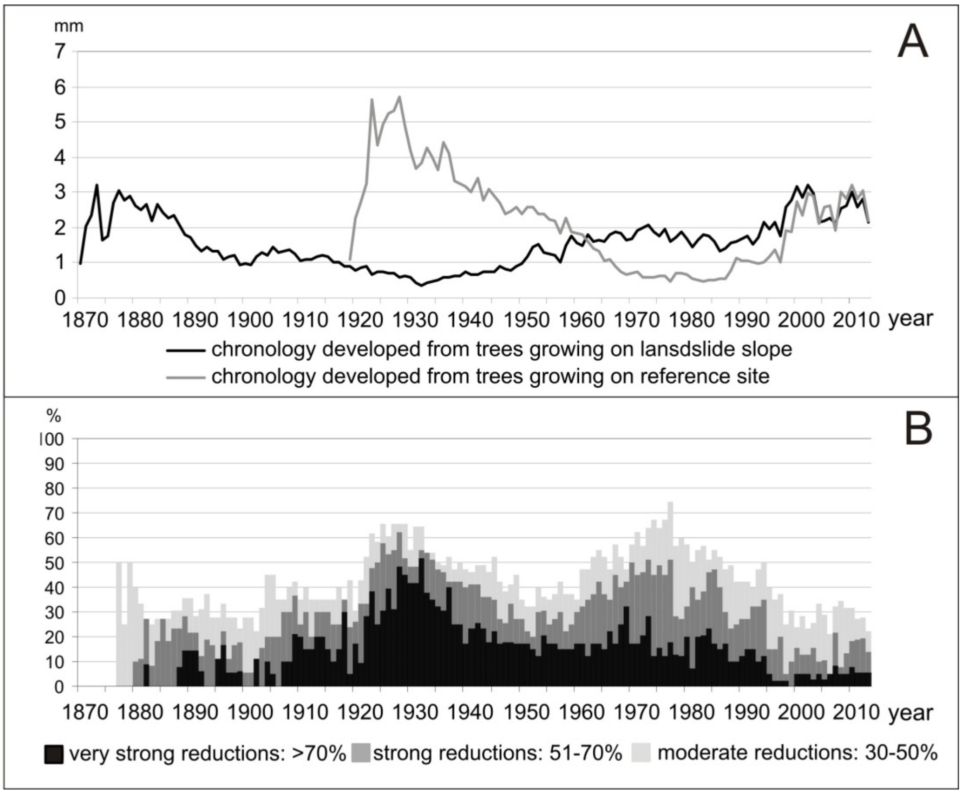

Figure 2: Chronologies and ring reductions calculated for sampled tress: A – chronologies developed from trees growing on landslide slope and on reference site, B – tree-ring reductions in all trees sampled.

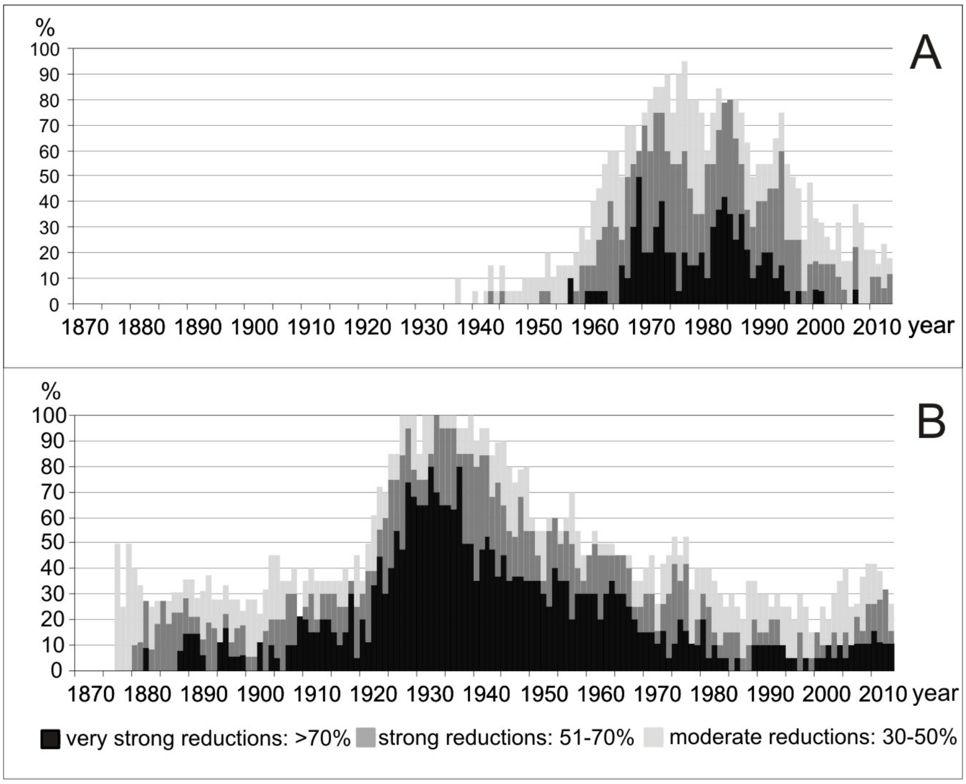

Figure 3: Tree-ring reductions calculated for trees growing on reference site (A) and on landslide slope (B).

Both periods with ring reductions (1920-1950 and 1960-1995) present in sampled trees are clearly visible on a graph showing percentage of trees with reduced rings in relation to a total of specimens sampled on landslide slope and reference site (Fig. 2B). Reductions which occurred in 1920-1950 are stronger than reductions from 1960-1990 (Fig. 3).

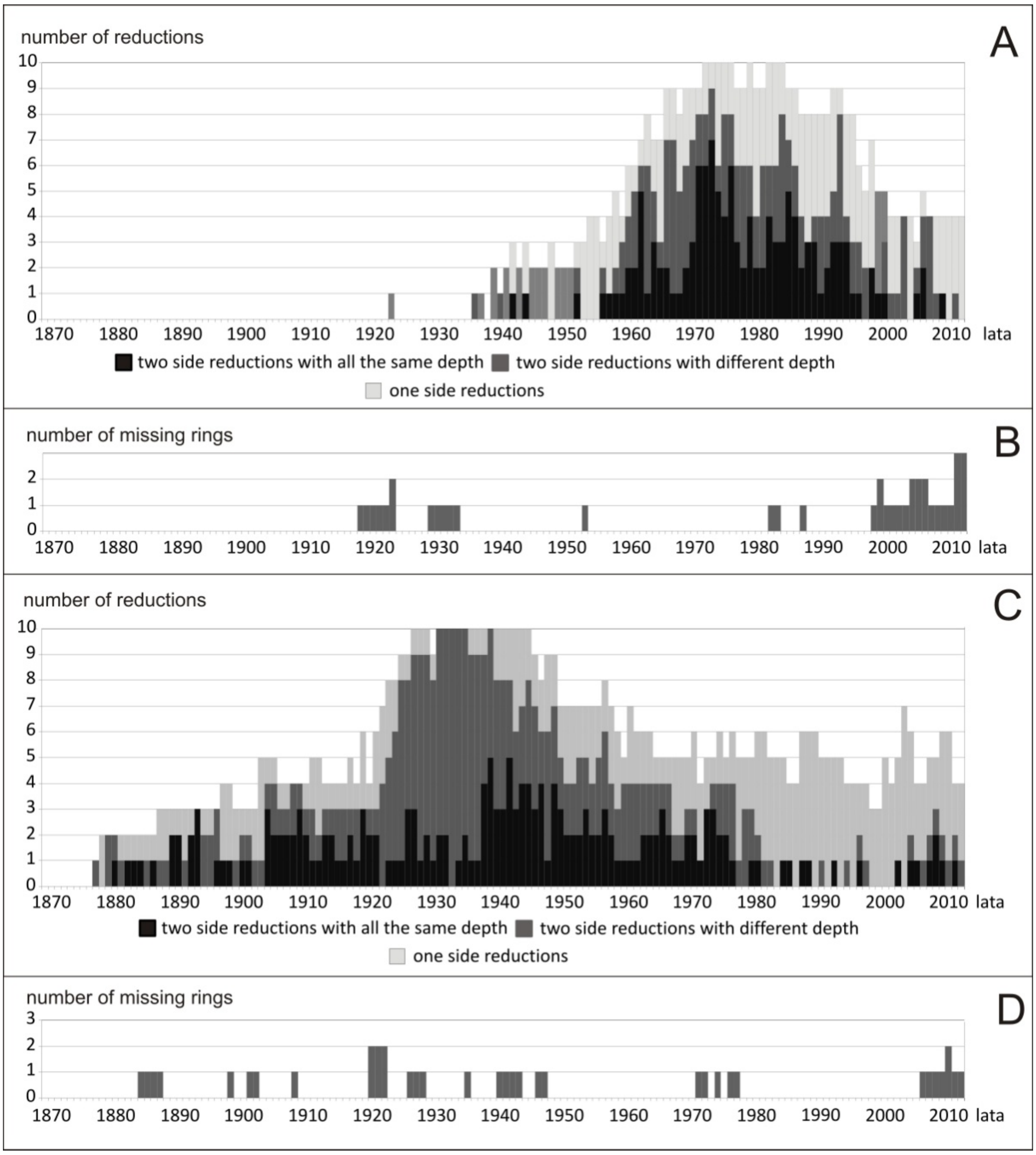

Figure 4: Tree ring reductions and missing rings, A – reductions calculated for trees growing on reference site, B – missing rings in trees growing on reference site, C – reductions calculated for trees growing on landslide slope, D – missing rings in trees growing on landslide slope.

In case of trees growing on the reference slope ring reductions on both sides of the stems with the same depth are clearly dominant (Fig. 4A). It is typical for firs developing reductions of annual rings due to air pollution. Trees growing on the landslide slope have developed much more one-sided reductions. This results from the eccentric growth related to landslide activity (Fig. 4C). In periods of heavy air pollution (1920-1980) firs growing on landslide slope have developed large number of two-sided ring reductions with a depth that differs between up- and downslope side of a stem (Fig. 4C). The effect described comes from overlapping stresses caused by air pollution (the same reduction on whole stem perimeter) with stresses caused by landsliding (reductions occur on one side of a stem). Since the 1980s, when air pollution decreased significantly one-sided reductions related to landslides dominate (Fig. 4C).

Missing rings occur in periods when two factors causing reductions (pollution and landsliding) overlap, mostly in: 1920-1950 and 1970-1980 (Fig. 4B, D). Missing rings occur also during the last 10 years, but the reason of their occurrence is unknown.

Conclusions

In case of trees growing on the landslide area and at the same time affected by air pollution there is a chance to recognize tree-ring reductions caused by pollution and landsliding. If the reductions occur on two opposite sides of a stem, according to slope inclination (up- and downslope), they were caused by air pollution emission. If the reductions are one-sided than they were caused by landsliding. In case when reductions are two-sided, but they occur with different depth then both landsliding and pollution are responsible for growth suppression (Fig. 5). Additionally in periods of simultaneous impact of air pollution and landsliding in studied trees we have identified missing rings, which record high environmental stress.

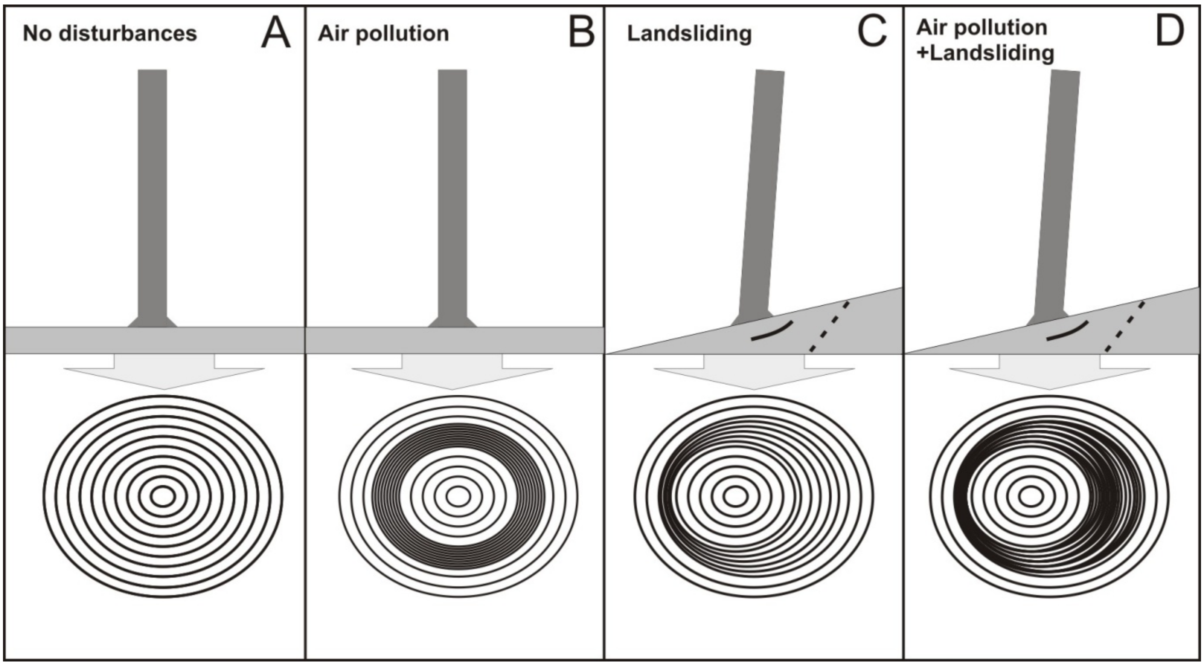

Figure 5: Comparison of tree-ring patterns formed as effects of landsliding and air pollution: A – tree ring pattern in trees growing without any influence of landsliding and air pollution, B – tree ring pattern in trees growing with influence of air pollution, C – tree-ring pattern in trees growing with influence of landsliding, D – tree-ring pattern in trees growing with influence of both landsliding and air pollution at the same time.

Acknowledgments

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SECTION 4

WOOD ANATOMY

Annual growth ring formation and growth rates of different tree functional types in a tropical mountain forest in Ethiopia

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Introduction

Dendrochronology in Africa is receiving increasing attention (Gebrekirstos et al. 2011, 2014), including an increasing number of tree species from different ecological zones (e.g. Couralet et al. 2010; DeRidder et al. 2013; Fichtler et al. 2004, 2010; Gebrekirstos et al. 2012; Trouet et al. 2006; Schöngart et al. 2006; Worbes et al. 2003). In Ethiopia, dendrochronologcial studies have been successfully carried out using different tree life forms, on several species of acacias (Gebrekirstos et al. 2009) and *Juniperus procera* (Sass-Klaassen et al. 2008; Wils et al. 2010, 2011). However, despite formation of annual tree-ring boundaries, the successful cross-dating of increment curves within one species can vary regionally according to the local precipitation regime (Wils et al. 2011, Gebrekirstos et al. 2014) and remains challenging due to the formation of missing rings or double rings (Krepkowski et al. 2012). Since little is known about species-specific growth behaviour and ecological functionality of different functional types of trees, we studied growth rates of a pioneer broadleaved deciduous tree (*Croton macrostachyus*, Euphorbiaceae) and a late successional evergreen conifer (*Podocarpus falcatus*, Podocarpaceae) with the help of electronic dendrometers (Krepkowski et al. 2011).

Study material and methods

Studied site and methods

The study site is located in a tropical mountain forest 240 km south of Addis Ababa at the eastern escarpment of the Main Ethiopian Rift Valley (7°26´N 38°53´E). Early successional stages within the natural forest are dominated mainly by *Croton macrostachyus* Hochst. ex Del whereas late successional stages contain a mixture of *Podocarpus falcatus*, *Celtis africana* Burm.f., *Syzygium guineense* (Willd.) DC., and *Prunus africana* (Hook.f.) Kalkman. Mean annual temperatures in 2.300 m altitude are 14.9°C and annual precipitation averages 1,225 mm, showing a bimodal rainfall pattern (Freier et al., 2010) with alternating rainy and dry seasons: a long rainy season from July to October is followed by a long dry season from November to February and an unreliable short rainy season from April to June, delimited by a short dry period in June (Krepkowski et al., 2011) that is occasionally missing due to a trend of increasing humidity in the recent years (Strobl et al. 2011).

From *C. macrostachyus*, five stem discs from trees that were cut in 2008 and increment cores were collected. Tree-ring boundaries in *Croton* are formed by a marginal parenchyma band and are only partly indistinct (Krepkowski et al. 2013), but it was possible to follow the ring boundaries across entire stem circumferences. Identifying ring boundaries on the increment cores was not successful. In total, 20 radii from the five stem discs were measured with a LINTAB V measuring table (Rinntech, Heidelberg, Germany). The final chronology was calculated using ARSTAN software by applying a cubic smoothing spline with a frequency cutoff of 50% at 2/3rd of the series length. We selected the residual chronology that was almost free of autocorrelation (AC (1) = -0.15) for comparison with local climate data that were measured since 2002 at a field research station less than 1 km distant from the study site.

Electronic point dendrometers (Ecomatik, Dachau, Germany) were installed in March and September 2008 at 1-1.5 m height on six stems of each species and radial stem diameter variations were registered in 30 minutes intervals. Short-term $^{13}CO_2$ pulse labeling of one individual *P. falcatus* and *C. macrostachyus* was carried out on two cloudless days (on November 12 and November 14, 2008) at the termination of the main rainy season. For the labeling experiment, 6 m high rectangular frames were constructed around the study trees, and ^{13}C-labeled CO_2 was generated by injecting diluted sulfuric acid into a flask containing isotopically enriched $Na_2{}^{13}CO_3$ solution (99 atom% ^{13}C). 12.5 mM of $^{13}CO_2$ per 1 m^3 was added to each chamber (0.73 moles $^{13}CO_2$ for 85 min. for *C. macrostachyus* and 0.89 moles for 105 min. for *P. falcatus*) (Krepkowski et al., 2013).

Results and discussion

C. macrostachyus forms annual ring boundaries allowing successful crossdating of 14 out of 20 measured radii. Table 1 shows the cross-dating results for averaged stem disc growth curves. The resulting chronology covers 34 years with a common period 1981-2008 (27 years) and is the first ring-width chronology developed from this species. Although this first chronology was too short to calculate common chronology statistics, the cross-dating results and the mean correlation between the ring-width series (r = 0.30) indicate that the individual tree-ring series of *Croton* can be confidently synchronized.

Table 1: Crossdating results for mean curves of five Croton macrostachyus discs. sign test results are significant on the p<0.01 level (italics) or the p<0.001 level (bold), respectively. t_{BP} = t-value after Bailie and Pilcher; CDI = cross-date index (Rinn 2003).

	time span	tree age	sign test*	t_{BP}	CDI
Cr_01	1975-2008	33	*72*	4.8	55
Cr_02	1975-2008	33	**91**	5.6	61.
Cr_03	1974-2008	34	*76*	3.8	36
Cr_04	1981-2008	27	**88**	5.0	51
Cr_05	1975-2008	33	**84**	4.0	50

* calculated against the mean curve of all trees

The final standardized ring-width chronology for *C. macrostachyus* is shown in Figure 1. Mean sensitivity, a measure of interannual chronology variability (Fritts 1976) is 0.45, indicating a strong common forcing on growth of *C. macrostachyus*. The length of the existing local climate data measurements does not allow final conclusions about the climatic forcing of the species' growth, but a correlation coefficient of 0.94 (p<0.001) gives a first indication that precipitation and thus water availability during the short rainy season (April to June) is critical for growth increment of *Croton*.

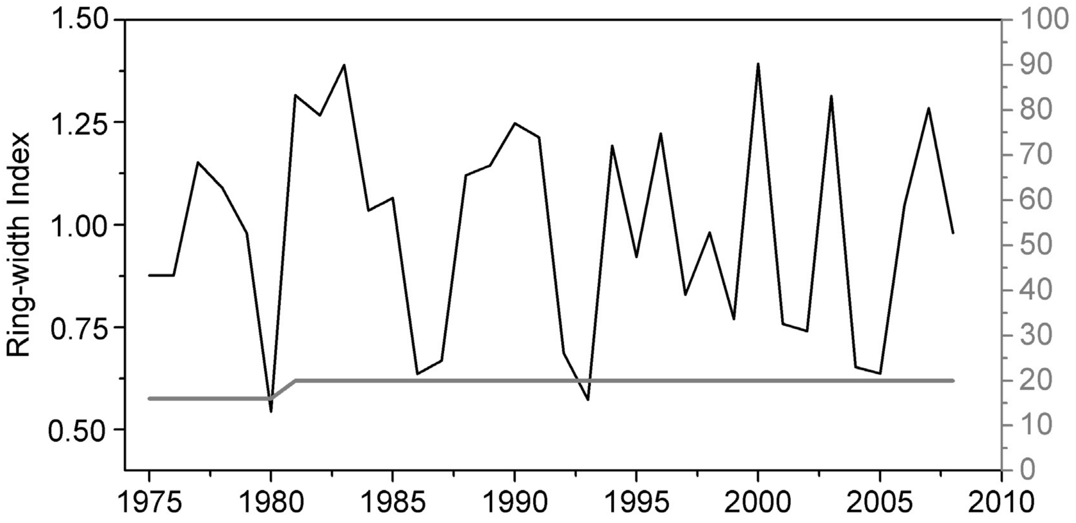

Figure 1: Residual chronology of Croton macrostachyus for the year 2005, measurement gaps do not allow the calculation of cumulative rainfall.

Average radial growth rates as indicated by point dendrometer measurements are compared in Table 2. During 2008-2011, *C. macrostachyus* showed higher increment with a wider range between individuals than *P. falcatus*, as it typical for a light demanding pioneer species. Mean growth of *C. macrostachyus* as derived from ring-width measurements on five stem discs is around 3.5 mm/year, indicting different growth rates in individual trees. In contrast to the deciduous *Croton*, the evergreen *P. falcatus* is able to start growth whenever moisture conditions permit (Krepkowski et al., 2013). Hence, it forms ring boundaries, but also density variations and false rings if several humid periods per year occur. Therefore we are not yet able to present a ring-width chronology with synchronized growth curves of several tree individuals from *Podocarpus*, yet.

Table 2: Average cumulative growth (ACG) of six individuals of Podocarpus falcatus and Croton macrostachyus measured by electronic dendrometers and of five C. macrostachyus ring width measurements (means of 1981-2008).

	n	measurement type	measurement period	ACG [mm]	growth range
P. falcatus	6	dendrometer	Mar 2008-Mar 2011	3.02	2.25-4.29
C. macrostachyus	6	dendrometer	Sep 2008-Mar 2011	4.27	1.64-6.92
	5	average ring width	1981-2008	3.51	2.75-3.94

The two species also differ considerably in their carbon storage behaviour: while the signature of enhanced δ^{13}C can be followed in *P. falcatus* for more than two vegetation periods, it quickly decays in *C. macrostachyus* (Krepkowski et al., 2013). We conclude that the various functional types of tropical trees differ in their cambial phenology and carbon carry over effects and growth rates. The varying strategies of carbon allocation between early successional and late-successional tree species have implications on plant-soil-atmosphere carbon balances of different forest successional stages, which have to be considered for carbon management of tropical forest landscapes. Determining the growth rate over the life of the tree is helpful in carbon stock accounting.

Acknowledgments

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Do we expect formation of growth rings on species with reverse phenology?

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Introduction

Faidherbia albida (Del.) A. Chev., a tree species belonging to the family Fabacea (subfamily Mimosoideae) is one of the most important species among the deciduous leguminous trees, and widely distributed in Africa and the Middle East (Barnes and Fagg 2003; Boffa 1994). The tree has a distinctive phenology: it bears leaves and flowers during the dry season and sheds its leaves during the rainy season (Barnes and Fagg 2003). The reason for the reverse phenology is not well known but the tree is known for its deep roots that might help it to access deep water sources during the dry season. Due to its reverse phenology the species is one of the key agroforestry species commonly retained by smallholders in their farming systems. Besides providing lifestock feed it favours crop production through improvement of soil fertility and soil water regulation without hampering crop growth through light competition due to its reversed leaf phenology (Barnes and Fagg 2003; Boffa 1994). Consequently, cereal cropping under *F. albida* has a long history in Africa (Bayala et al., 2012; Saka et al. 1994) and this is particularly common in what are called Faidherbia parklands in the Sahel and southern Africa (Boffa 1994).

Faidherbia is common in many river valleys and along lakeshore plains (Barnes and Fagg 2003). Farmers have traditionally retained and protected *F. albida* trees on their fields for centuries as an intercrop to boost maize yields (Henry et al. 2009). Estimation of above-ground biomass is an essential aspect of carbon stock and carbon sequestration determination (Ketterings et al. 2001). There is increased interest in estimating the biomass of trees and their role in regulating the cycling of carbon and nutrients (Cairns et al. 1997). In the context of climate change In recent years, carbon sequestration potential of mixed tree cereal cropping systems have recently attracted attention from both industrialized and developing countries following the recognition of trees on farms as a greenhouse gas mitigation strategy under the Kyoto Protocol (IPCC 2000, Makundi and Sathaye 2004). The sale of carbon sequestered through trees on farms to industrialized countries could be an attractive opportunity for subsistence farmers in developing countries in Africa who are the major practitioners of mixed tree cereal cropping systems. Hence, there is need to assess *F. albida* trees on the farmers' fields as well.

Over the last decade it has become clear that annual rings are formed in many tropical forest trees (Worbes 2003; Gebrekirstos et al. 2008; 2009, Brienen & Zuidema 2006, Wils et al. 2011), thus providing an opportunity to study lifetime growth and age in a direct and more reliable way. Tree-ring analysis (dendrochronology) produces annual diameter increments by retrospective analysis over the whole lifespan of a tree (Brienen & Zuidema 2006, Schöngart et al. 2011, Gebrekirstos et al. 2014). Hence, the main objectives of this study are to 1) explore if *F. albidia* forms distinct rings, and 2) determine tree age and average growth rates of *F. albida* by tree-ring analyses.

Methods

We collected samples of in total 24 *F. albida* trees from Malawi, southern Africa. *F. albida* trees in the parkland cropping system are found scattered in cultivated fields, where agricultural crops are intercropped under them (fig. 2a). In June, July and October 2010, 5 to 7 *F. albida* trees were selected across four locations (Bwanje, Karonga, Mwanza and Salima) based on DBH class distribution. The study location and the basic characteristics of these sites are summarized in Fig. 1 and Tab. 1, respectively. Trees that had been pruned by the owners and that showed severe defects were not sampled. The trees were cut for parallel biomass estimation by (Beedy et al. in preparation).

Figure 1: Location of the parkland Faidherbia albida study sites, Malawi

After sanding the stem discs (up to grit size of 800), we counted and measured tree rings in two to four radii and calculated annual diameter growth rates by averaging ring widths from those radii. Radii were chosen such that the average of the radii best corresponded to the calculated average diameter of the disc.

For each tree we established age-diameter relationships for its complete lifetime. Note that the ages presented here are calculated from stem discs obtained at >30cm above the ground and do not include the time required to grow from seedling to sampling height. This means that both average age and its variation are underestimated. The time to reach the minimum sampling height is probably about 3 years. We fitted a logistic curve to the data relating DBH to estimated tree age (years).

Table 1: Location and *characteristics of study sites, number of sample trees*

Name	Landform	Rainfall (mm)	Elevation (m)	n	Geo-reference
Bwanje	river valley	1100	619	8	14°38′S, 34°46′E
Karonga	lakeshore plain	1300	496	8	10°04′S, 33°59′E
Mwanza	river valley	1100	496	8	15°17′S, 34°56′E
Salima	lakeshore plain	1300	529	7	13°36′S, 34°18′E

Result and discussion

F. albida (Fig 2a) in Malawi forms growth boundaries characterised by alternating fibre and parenchyma bands and density differences between early and late wood (Fig 2b). Early wood could be distinguished from latewood by its wider parenchyma cell lumina, band width and thinner walled fibres. The stem disks are very light in weight and the vessels are almost visible to the naked eye. Although, formation of growth boundaries were reported in many tropical tree species, formation on growth boundaries in *F. albida* was not so far reported. Given the seasonality in climate and distinct growth boundaries, the rings are most likely annual.

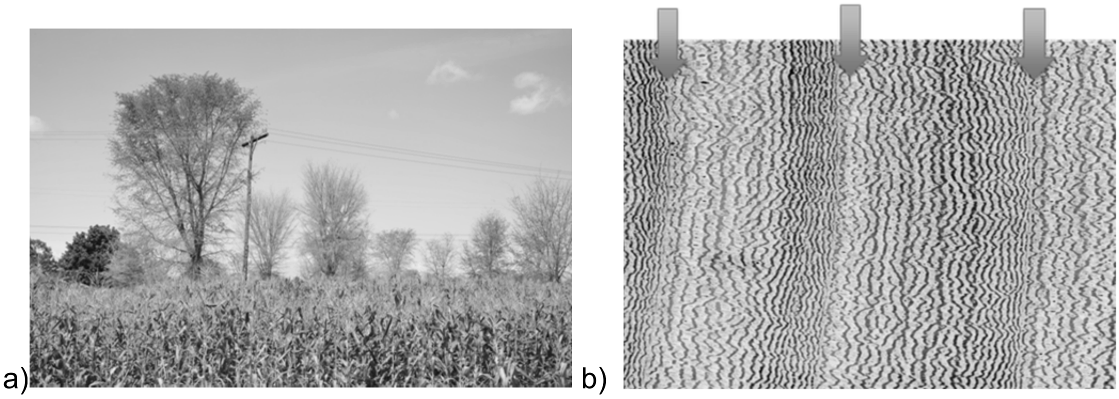

Figure 2: a) Faidherbia albida,Fabaceae leafless during rainy season in January (photo credit G.W. Sileshi) and b) Cross-section of Faidherbia albida. Arrows indicate distinct growth boundaries.

There is a substantial gap in fundamental knowledge concerning how agroforestry species grow in response to climate variability, and therefore how they might react to future climatic change. The sampled *F. albida* trees were fast growing. The annual growth rate varied considerably between years ranging from 1.37 mm to 17.72 mm with a mean growth of 9.34 mm . Age structure of the trees indicated that the majority of trees reach D > 20 cm when 10 years old and the majority of the trees were between 10 and 20 years old. The logistic curve relating DBH with estimated tree age showed a good fit (Fig 3a). Larger variability in DBH is predicted towards the upper end of the curve. However, the residuals show no systematic variation (Fig 3b). The age–diameter relationship appears to vary strongly between individuals than among comparable site conditions (Table 1). The fast growth of *F. albida* shows its additional potential for carbon sequestration.

Tree rings are valuable tool to analysis climate growth relationships to asses drought tolerance (e.g Gebrekirstos et al 2008, 2012, Fichtler et al. 2006, Trouet et al. 2006, Sass-Klaassen et al. 2008) and water use efficiency (Gebrekirstos et al. 2011). Hence, the fact that *F. albida* forms a ring is an opportunity to analyse it relationship with climate parameters and make informed decision in promoting *F albida* for agroforestry in other regions. The acquired information from tree rings versus age and long-term growth rates can be directly applied to estimate growth yields (above ground carbon stock) with relatively simple models. Hence, tree ring analysis could be a valuable and reliable tool to project carbon stocks (Schöngart et al. 2011, Gebrekirstos et al. 2014).

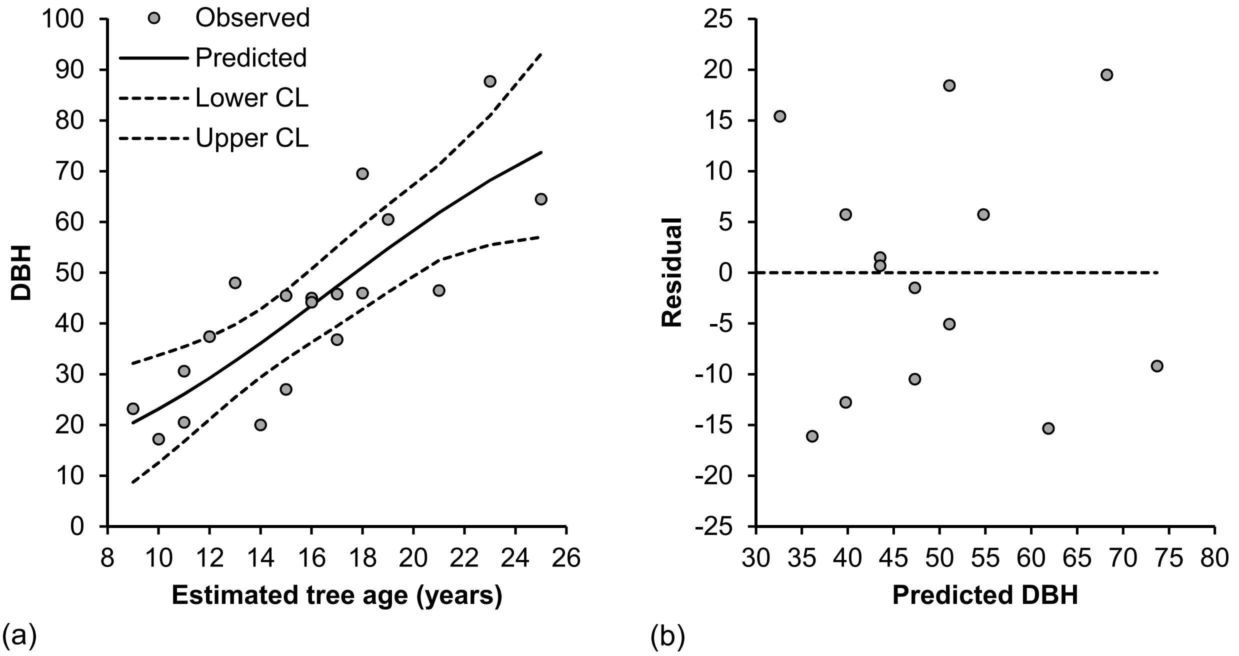

Figure 3: The relationship between stem diameter (DBH) and estimated tree age of Faidherbia albida across sites (a) and the residuals from the fitted model (b). The dashed lines in (a) represent the upper and lower 95% confidence limits of the logistic curve.

The project is ongoing and will strive to identify the climate growth relationships and the triggering factor for its reverse phenology. Formation of growth boundaries is evident in all study localities within Malawi but we recommend further studies before making generalizations about the behaviour of the species in its entire distribution range. There is also a dire need to understand the hydrological preferences, under natural conditions in space and time.

Acknowledgements

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Wood and phloem formation in beech (Fagus sylvatica)

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Introduction

The increasing need to better understand the physiological processes of trees in response to environmental conditions, and the consequences of these conditions on wood quality, require comprehensive wood-formation studies in different environments all over the world (Deslauriers et al. 2003, Rossi et al. 2003, Gričar and Čufar 2008) not only on cellualr but also on sub-cellular and ultrastrucutral level. These studies can build a link between different disciplines dealing with the environment, forests, trees and wood (Fonti and Jansen 2012).

Wood with its various cell types is produced by the cambium, and its quality is to a great degree defined during its formation and subsequent developmental processes. In addition, cambium produces phloem which translocates products of photosynthesis and is consequently crucial for tree survival. Nevertheless, phloem formation has so far been less investigated, partly also because of its lower economic importance.

Studies on beech (*Fagus sylvatica*) have shown relations between cambial activity, tree-ring width/anatomy variation and leaf phenology (Čufar et al. 2008b, Čufar et al. 2012). These processes are affected by climatic change which is especially pronounced in Slovenia, a transitional area between the Mediterranean, Alpine and continental climatic regimes (de Luis et al. 2012).

The aim of our contribution is to overview the main results regarding xylem and phloem formation in beech (*Fagus sylvatica*) from sites in Slovenia, with an emphasis on observations at different levels, e.g. cellular, sub-cellular and ultrastructural one.

Materials and methods

Investigations in beech (*Fagus sylvatica* L.*)* were performed on mature forest trees from two areas with temperate and Alpine climatic regimes in Slovenia: Panška reka near Ljubljana (400 m a.s.l.) and Menina planina in the Alps (1200 m a.s.l.) (e.g. Prislan et al. 2013b). The low-elevation site is representative of a large part of beech sites in Slovenia (Čufar et al. 2008a). The high-elevation site is located near the altitudinal limit of beech distribution in the Slovenian Alps. Investigations were conducted between 2006 and 2011. Similar studies still continue.

At both sites leaf phenology was observed as well. The dates of leaf unfolding and autumnal leaf colouring were recorded for the selected trees. The observations were made in accordance with Guidelines for plant phenological observations (Koch et al., 2007). All samples (inner bark, cambium, and outer xylem) were collected at weekly intervals from stems of living trees (at breast high) by the intact tissue sampling method (Gričar et al. 2007) or by micro-coring (Rossi et al. 2006). Immediately after removal from the trees, the samples were fixed in a solution of formalin, ethanol and acetic acid (FAA) and embedded in paraffin. Approximately 12 µm thick transverse sections were prepared using a rotary microtome, and stained with safranin and astra blue. The sections were examined with a light microscope (LM) (Fig. 1a, b, c). Different stages of xylem growth ring formation / cell differentiation were determined using bright field and polarised light (e.g. the phase of postcambial growth and the phase of secondary cell wall synthesis could be

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most clearly seen under polarized light). The number of cell layers in the cambium and the widths of xylem and phloem growth rings were measured with an image analysis system.

Detailed ultrastructural and topochemical analyses of xylem, phloem and cambium were performed with a UV – microspectrophotometer (UMSP) (Fig. 2) and a transmission electron microscope (TEM) on samples embedded in epoxy resin. Depositions of cell-wall layers in xylem and phloem cell walls were observed with TEM on ultra–thin (90 – 100 nm) sections stained with potassium permanganate (Fig. 1e). In addition, lignin contents in xylem and phloem cell walls were determined semi-quantitatively on semi–thin sections (1 µm) with UMSP. For observation of seasonal ultrastructural changes in cambial cells, samples were prefixed with a glutaraldehyde/paraformaldehyde solution, postfixed with osmium tetroxide, and embedded in epoxy resin. Sections were then stained with uranyl acetate and lead citrate (Frankenstein et al. 2005) and examined by TEM (Fig. 1d).

Results and discussion

The results show that at the low-elevation site the production of new xylem cells in cambium in the period between 2006 and 2011 always started in the first half of April. The maximum rate of xylem-cell production occurred at the beginning of June. Cessation of xylem production was observed in mid-August. The patterns of wood-formation processes were similar at both locations, but there were differences in their timing. At the high-elevation site production of new cells started on average 1 month later than at the low elevation site, i.e. in mid-May, and maximum cell production occurred around the summer solstice. Xylem production at high elevation ceased slightly earlier than at the low elevation, i.e. in the first part of August. As a consequence, xylem increments were on average two times higher, and variation between different years was larger in trees at the low-elevation site in comparison to high elevation site (Čufar et al. 2008b, Prislan et al. 2013b).

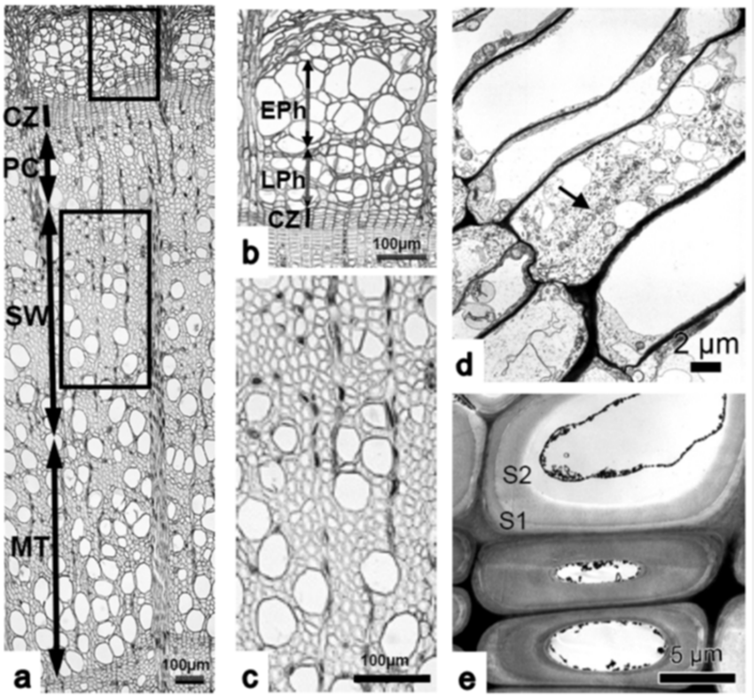

Figure 1: Xylem, cambium and phloem of Fagus sylvatica in different phases of development: (a) cross-section of the cambium (CZ) and developing xylem with cells with primary wall (PC), with developing secondary cell wall (SW), and mature cells (MT); (b) cambium and last formed non-collapsed phloem with early- (EPh) and late phloem (LPh); (c) SW cells –detail; (d) TEM image of active cambial cells, arrow points to new formed cell plate; (e) TEM image of developing fibre containing S1 and S2, below two mature fibres.

UMSP and TEM analysis of xylem cell wall formation were carried out in 2008 at the low elevation site Panška reka. These two approaches enabled detailed insights into the processes of cell-wall thickening and lignification of xylem cells (Fig. 1e, Fig. 2). Lignification generally started 1-2 weeks after the formation of the first new cells. The process of differentiation in the first formed xylem vessels was finished one month after the onset of cell production in the cambium. However, differentiation of the first formed xylem fibres lasted for approximately two months. After the cambial cell division was finished, between the beginning and mid August, the differentiation of the terminal fibres continued for another four weeks. Vessel walls were characterised by a larger amount of strongly absorbing guaiacyl lignin, whereas fibre walls contained more syringyl units. The content of guaiacyl lignin was also higher in the terminal part of the annual ring. Different lignification dynamics in initial and terminal parts of the growth ring can be linked with the different chemical structure of lignin in cell walls of vessels (with a higher amount of syringyl lignin in the terminal part) and fibres (with a higher amount of guaiacyl lignin) (Prislan et al. 2009).

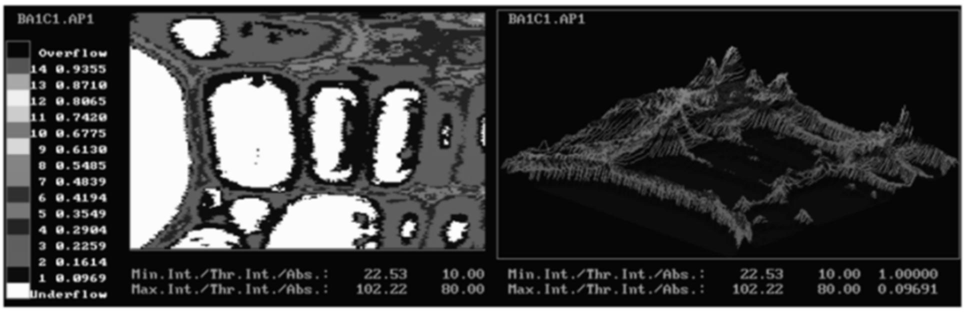

Figure 2: UMSP images of developing xylem fibres and vessels of Fagus sylvatica; the figure shows absorption values in fibre and vessel cell walls in the initial part of the growth ring in the middle of May (at the low elevation site). Different colours represent different absorption values; higher absorption values are related to higher lignin concentrations and vice versa. Since lignification starts first in cell corners (CC) and middle lamella (ML), the absorption values of these regions are higher. In S1 and S2 layers of the fibre cell walls the absorption values are low at that time because the lignification process is not finished yet, however in vessels the lignification process is almost finished. Legend – UV absorption at a wavelength of 280 nm and optical resolution of 0.25 µm x 0.25 µm.

Studies on the dynamics of phloem formation at low and high elevation sites revealed that the first new phloem cells were produced by the cambium at approximately the same time as the first xylem cells. However, phloem formation obviously started with the differentiation of 1-2 phloem cells which overwintered. The preparation techniques enabled us to produce microscopic slides where early phloem, late phloem and the phloem-ring boundary could be distinguished in the youngest non-collapsed phloem growth ring (Fig. 1b). It was shown that the collapse of early phloem sieve tubes occurs soon after the cessation of the cambium in August, indicating that at the breast height where the samples were taken they remain functional only during the current growing season (Prislan et al. 2012). The analysis of bark tissues showed that the proportion of sclereids increased with the age of the phloem. The chemical composition of lignin in sclereid walls proved to be similar to lignin in xylem-fibre walls; however, lignin concentration was higher in sclereids (Prislan et al. 2012).

The active cambium always contained more cells per radial row than the dormant one. Observations with TEM, revealed differences in the ultrastructure of cambial cells (Fig. 1d). We were able to differentiate between the phases of dormancy, reactivation, activity and transition to dormancy. Active cambial cells contained large central vacuoles, whereas the other cell organelles aggregated in narrow cytoplasmic strands attached to the cell wall. Furthermore, the cells contained thin walls, active dictyosomes with visible secretory vesicles, numerous spherical or oval-shaped mitochondria, mainly rough endoplasmatic reticulum of cisternal form, and numerous plastids containing starch. Often newly forming cell walls could be seen in the middle of the dividing cambial cells (Fig. 1d). Cells in the dormant cambium were characterized by slightly thickened radial and tangential cell walls and contained lipid droplets. Plastids containing starch were rare, cytoplasm became denser, and the vacuoles were smaller and more numerous. According to these ultrastructural changes, cambial activity at both, the low and the high elevation site, started approximately one month earlier than determined by light microscopy (Prislan et al. 2011, Prislan et al. 2013a).

We showed that the onset of xylem and phloem cell production by the cambium coincided with leaf unfolding. According to long-term data (1955-2007), collected by the Environmental Agency of the Republic of Slovenia (ARSO), leaf unfolding in *Fagus sylvatica* is positively correlated to March temperatures at low elevations and with April temperatures at high elevations. As a consequence of climatic warming, significant trends towards earlier leaf unfolding were observed especially at high elevations (Čufar et al., 2012).

Comparison of results obtained by wood and phloem formation and leaf phenology studies can improve our understanding of the impact of environmental factors on radial growth in *Fagus sylvatica.*

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Vertical variability of tree-ring eccentricity in stems of Scots pine trees (*Pinus sylvestris* L.)

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Introduction

Growth eccentricity is a tendency of a tree to produce annual rings wider on one side of a stem and narrower on the opposite side. Producing eccentric rings is connected with uneven distribution of strains within a stem (Yamaguchi et al. 1980, Timell 1986, Kwon et al. 2001, Du et al. 2004), e.g.: after tilting from vertical position (Braam i in. 1987a, 1987b, Schweingruber 2007), as a result of crown asymmetry or asymmetry of root system (Krzysik 1974). Eccentric tree growth, which might be caused by diverse environmental factors is also frequently used as an indicator in dendroecological (e.g. Krzysik 1974, Wade & Wendel-Hewson 1979, Burkhalter *vide* Schweingruber 1996, Mäkinen 1998, Stokes & Berthier 2000, Berthier et al. 2001) and dendrogeomorphological studies (e.g. Braam et al. 1987a, 1987b, Krąpiec & Margielewski 2000, Casteller et al. 2007, 2008, Koprowski et al. 2010, Wistuba et al. 2013).

The knowledge about the relation between developing eccentricity and developing reaction wood is limited so far (Schweingruber 1996). Koprowski et al. (2010) show that eccentricity among Scots pines (*Pinus sylvestris* L.) might be formed even a few years earlier than reaction wood. The authors claimed that it could be an effect of the different stress thresholds, lower for eccentricity than in case of reaction wood formation. This suggests that developing eccentricity may require smaller strains inside a stem than in case of compression wood.

Moreover, the exact individual conditioning of eccentricity development have not yet been diagnosed: its dependence on age, tree size, stem shape and the angle of stem inclination. Only few analyses have been made on the topic (e.g. Mäkinen 1998). No studies on vertical diversity of eccentricity formation along tree stems have also been carried out so far. The problem how eccentricity of tree rings change along single stem is a subject of preliminary work presented in this paper. The aim of the study was (1) to analyse the vertical variability of eccentricity in stems of two selected Scots pine (*Pinus sylvestris* L.) specimens and (2) to check what is the connection of vertical variability with mechanical features of the tree as a whole, its habit, size and with the impact of external stress factors. For the study we chose trees growing in a dense forest stand, on a flat surface, stable from the geomorphic point of view, in the upland area devoid of external factors which could strongly influence radial growth, e.g. permanent winds from one direction, landslides, soil creep and snow cover movements.

Study area

Sampled trees were growing in an upland area located in Central Europe, in southern Poland, in Lesser Poland Voivodeship, about 45 km NW from Cracow and 1.3 km NNE from Klucze. Study site is located on Silesian-Cracovian Upland (Fig. 1).

Sampled trees were growing in a forest stand located 330-380 m a.s.l., on a gentle slope with northwestern aspect and average inclination of about 13%. Bedrock is composed of Mesozoic carbonate rocks, mostly limestones (Stupnicka 1989), only locally occurring in outcrops. Most of the ground surface is covered by Quaternary sands (Kondracki 1998). Average yearly temperature in the upland area under study reaches 8ºC. Winter in the study area lasts 80 days, summer 80-85 days and vegetation period 220 days (Šafár et al. 2003). Precipitation in the area usually exceeds 600 mm per year and is relatively high because of the high altitude of the area above sea level. Snow cover lasts long, over 80 days per year (Stopa-Boryczka & Boryczka 2005).

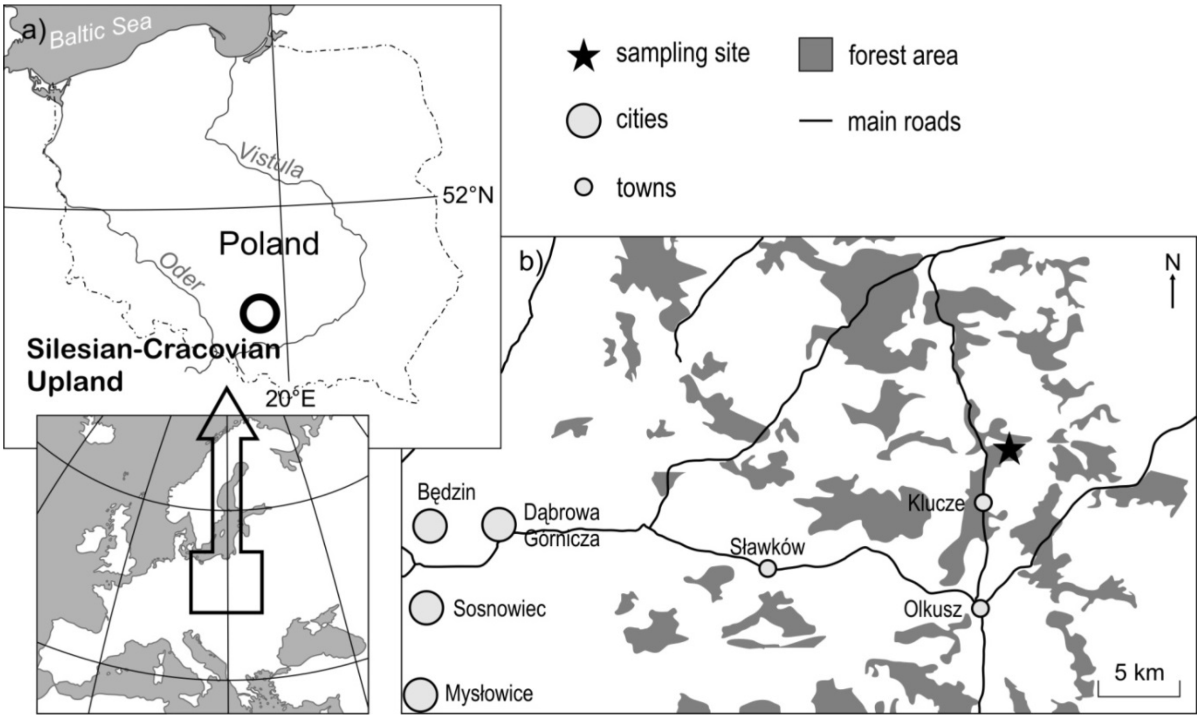

Figure 1: Location of the sampling site a) in Central Europe and Southern Poland, b) NNE from the Klucze town.

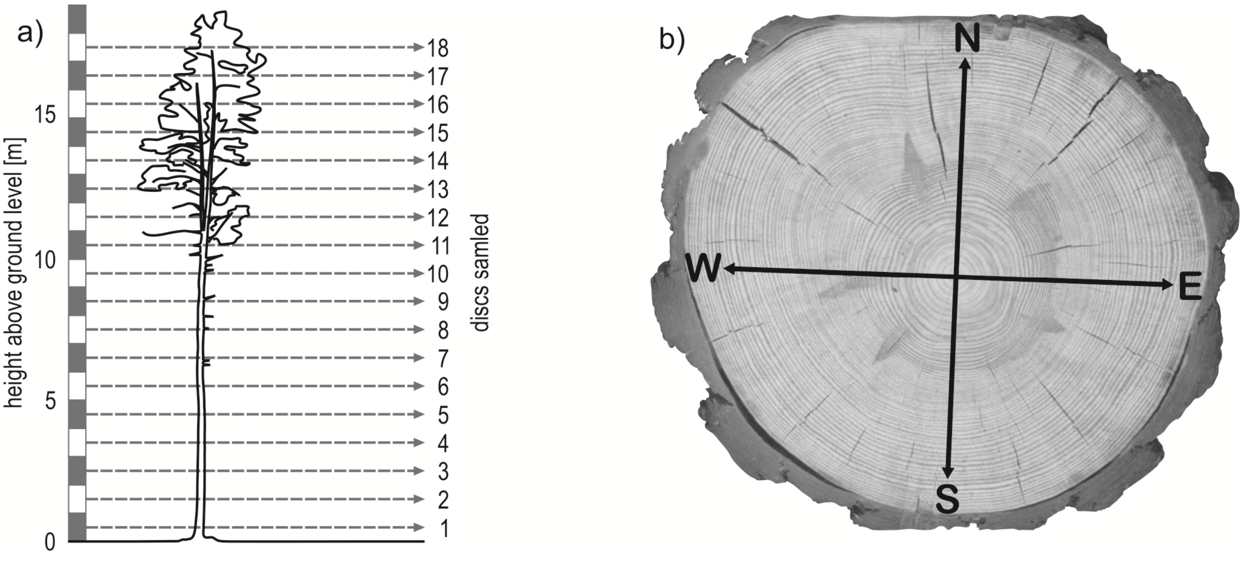

Figure 2: a) Disc sampled from pine stems. b) An example of disc sampled from tree A (disc number 2) with N-S, W-E axes marked.

The tree stand in which sampled specimens of *Pinus sylvestris* L. were grown is a human-planted, even-aged pine forest. Only limited areas on limestone outcrops are covered by beech forest. Less than 2 km SW from the study site is located the Błędowska Desert, an area partially devoid of vegetation cover and with open sands.

Materials and methods

Two mature specimens of Scots pine (trees A and B) were studied. From each tree stem we sampled 18 discs (from 19.9 to 1.7 cm in diameter – tree A, from 22.7 to 2.0 cm in diameter – tree B) at 1 meter intervals starting 0.5 meter above the ground (Fig. 2). We weighted all discs and measured their perimeter. We weighted segments of tree stems between discs as well, together with all branches. Next the samples were polished using sanding paper. We measured widths of annual rings for all 36 discs along pairs of perpendicular axes (N-S and W-E directions, Fig. 2) (LinTab measuring station, TSAPWin Professional 4.65 software, 0.01 mm precision). Sequences of tree-ring widths obtained for each tree were compared one with another using skeleton plots, which allowed us to find rings wedging in single stem cross-section and tree-rings partially missing along stem height (present only in some discs and completely absent in another).

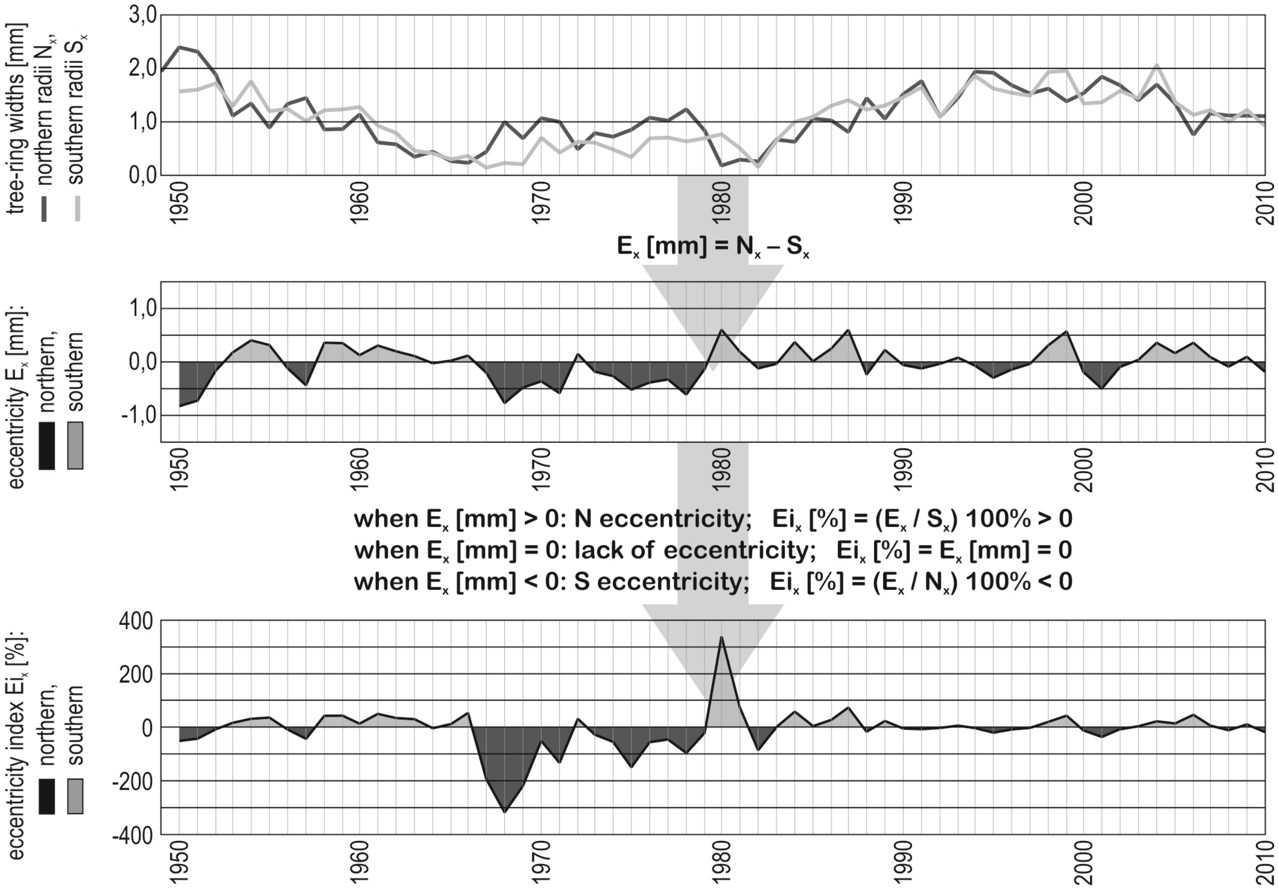

Figure 3: Transformation of tree-ring widths into eccentricity [mm] and eccentricity index [%] – example of the lowest disc (n. 1) in tree A, N-S axis;
N – width of tree-rings in the northern part of the stem [mm]; S – width of tree-rings in the southern part of the stem [mm]; E – eccentricity of tree-ring [mm]; Ei – eccentricity index of tree ring [%]; x – year.

By using tree-ring widths obtained for all discs and all measuring axes we calculated the following eccentricity parameters: eccentricity [mm] and eccentricity index [%] (Fig. 3). We used a method of eccentricity analysis described by Malik & Wistuba (2012), Wistuba et al. (2013). Eccentricity was calculated as a difference between northern and southern radii, next recalculated into per cents according to formula presented on Fig. 3. We analysed vertical variability of tree-ring widths in stems and vertical variability of eccentricity index values. For selected single years/rings we have analysed the vertical variability (in consecutive discs) of eccentricity index in relation with the vertical changes in number of growth rings in discs, their perimeters and weight of the section of a tree above each disc. We compared the values of the eccentricity index obtained in two perpendicular axes in both trees.

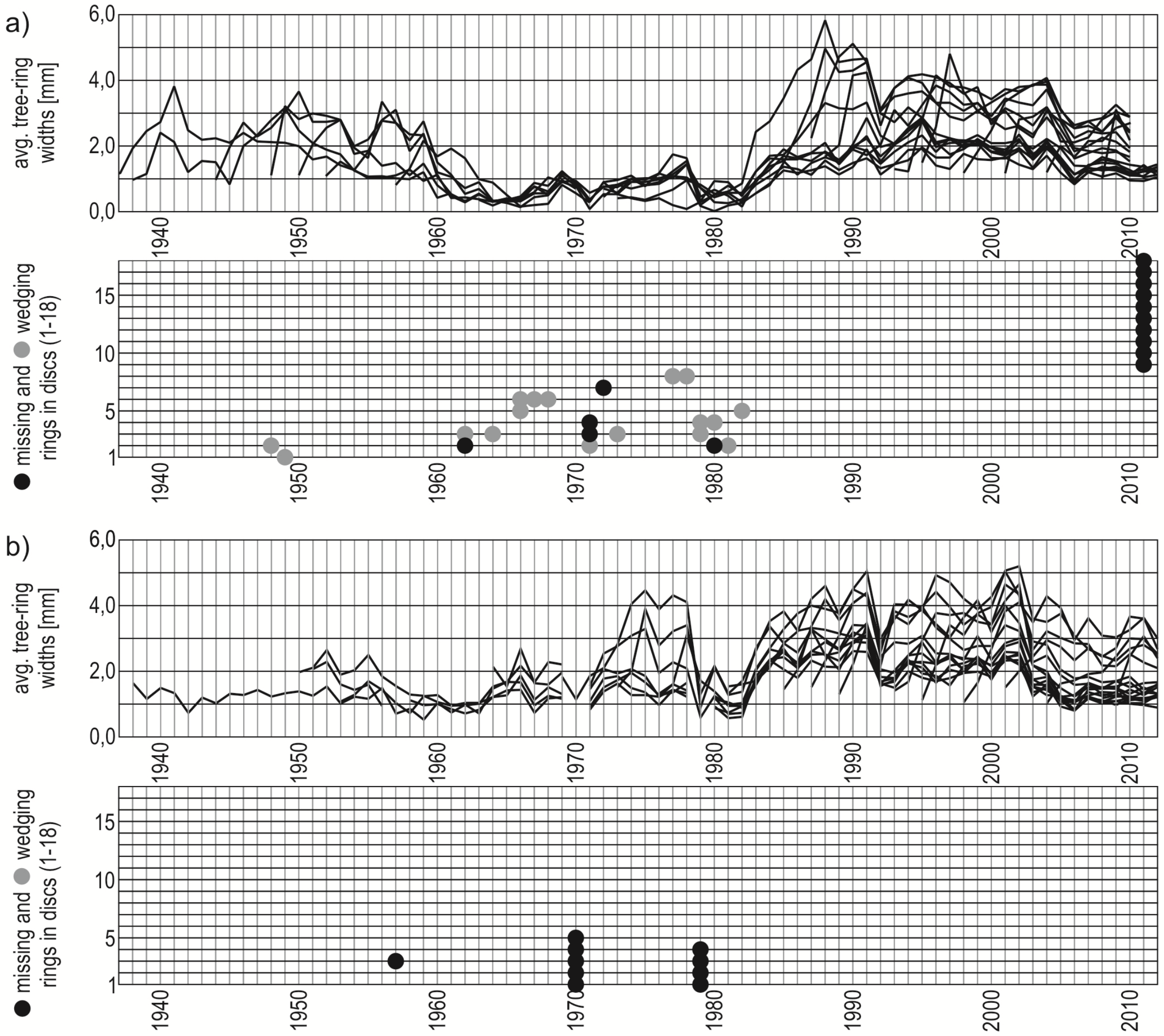

Figure 4: Tree-ring widths (avg. values from N, S, W, E axes), missing in wedging rings in all discs sampled (black and grey dots, missing values on tree-ring curves): a) tree A, b) tree B.

Results and discussion

By analysing numbers of annual rings in discs sampled from the lowest parts of stems studied (0.5 m above the ground, Fig. 2, 3) it was found that the studied specimens have the same age. At the stem base of Scots pine trees A in 2012 we have found 76 rings (the oldest: 1937), and in case of tree B: 75 rings (the oldest: 1938, Fig. 4).

Tree-ring series in both stems obtained from all discs (avg. values for four radii: N, S, W, E in each disc) correlate well with one another. It can be confirmed both by visual analysis of graphs (Fig. 4) and by high level of correlation coefficients for pairs of consecutive discs (tree A: 0.67 on average; tree B: 0.70 on average).

There is a clearly poorer correlation between sequences of eccentricity index values calculated for all discs in each tree (e.g. Fig. 5: W-E axis in all discs of both trees). Comparing them on graphs we have found strongly divergent patterns of curves. Values of correlation coefficients calculated for pairs of consecutive discs are low (tree A: 0.14 avg., tree B: -0.03 avg.).

Results show that the pattern of eccentricity along spruce stems is poorly synchronized than in case of raw tree-ring widths. This suggest a complex character of mechanical stress affecting stems of studied pines, despite that they grow in the area devoid of strong environmental factors disturbing radial growth. Yet the reaction of both studied pines to mechanical stress seems to be complex and the pattern of eccentricity developed differs along the stems.

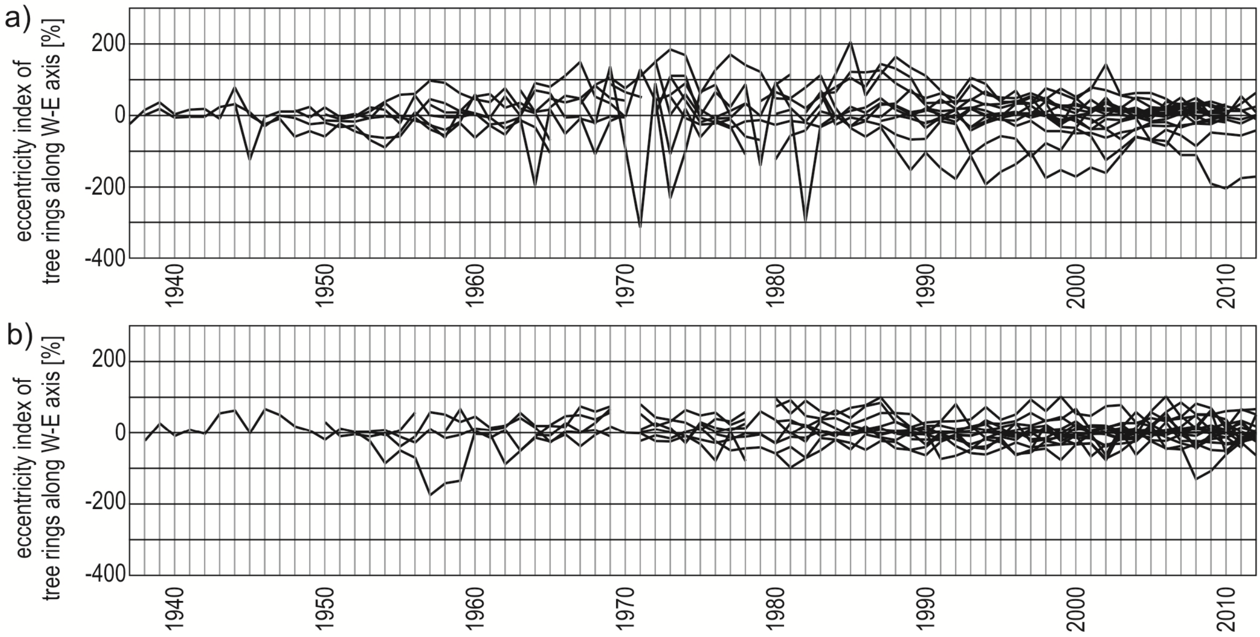

Figure 5: Eccentricity index values calculated for W-E axes in all discs sampled (missing values on tree-ring curves – missing or wedging rings): a) tree A, b) tree B.

Eccentric growth pattern is also displayed through development of wedging rings (with incomplete perimeter, where ring width in some part of perimeter equals 0.0 mm). In studied *Pinus sylvestris* L. specimens we found both the presence of rings that wedge within one stem cross-section (incomplete perimeter within one disc, e.g. Fig. 4a rings produced in 1966-68, disc 6, tree A) and the presence of rings that wedge vertically, present only in some of sampled discs and missing completely on the whole perimeters of other discs (e.g. Fig. 4b year 1970, discs 1-5, tree B).

We have studied vertical variation of eccentricity of single annual rings (Fig. 6) along stems of pines A and B in order to analyse in detail the mechanical relationships which cause the occurrence of: above mentioned chaotic pattern of eccentricity and rings that wedge laterally and vertically in relation to stem shape. Vertical variability of eccentricity in both Scots pines was analysed for three age ranges (Fig. 6):

1. 15 years old trees (we analysed rings produced in 1951 – tree A and in 1952 – tree B),
2. 40 years old trees (we analysed rings produced in 1976 – tree A and in 1977 – tree B),
3. 65 years old trees (we analysed rings produced in 2001 – tree A and in 2002 – tree B).

In Fig. 6 we marked values of eccentricity index in these years in single consecutive discs from the ground level upwards (from 1 to 18). We included results for two perpendicular axes: N-S and W-E. We found that eccentricity occurs in both axes studied and its vertical changes are often abrupt. Changes of the direction of eccentricity between two consecutive discs occur very often (e.g. tree A at the age of 65, W-E axis: eccentricity index in disc 3: -121% ring wider on the eastern side of stem, above in disc 4: 148% ring wider on the western side of stem, Fig. 6).

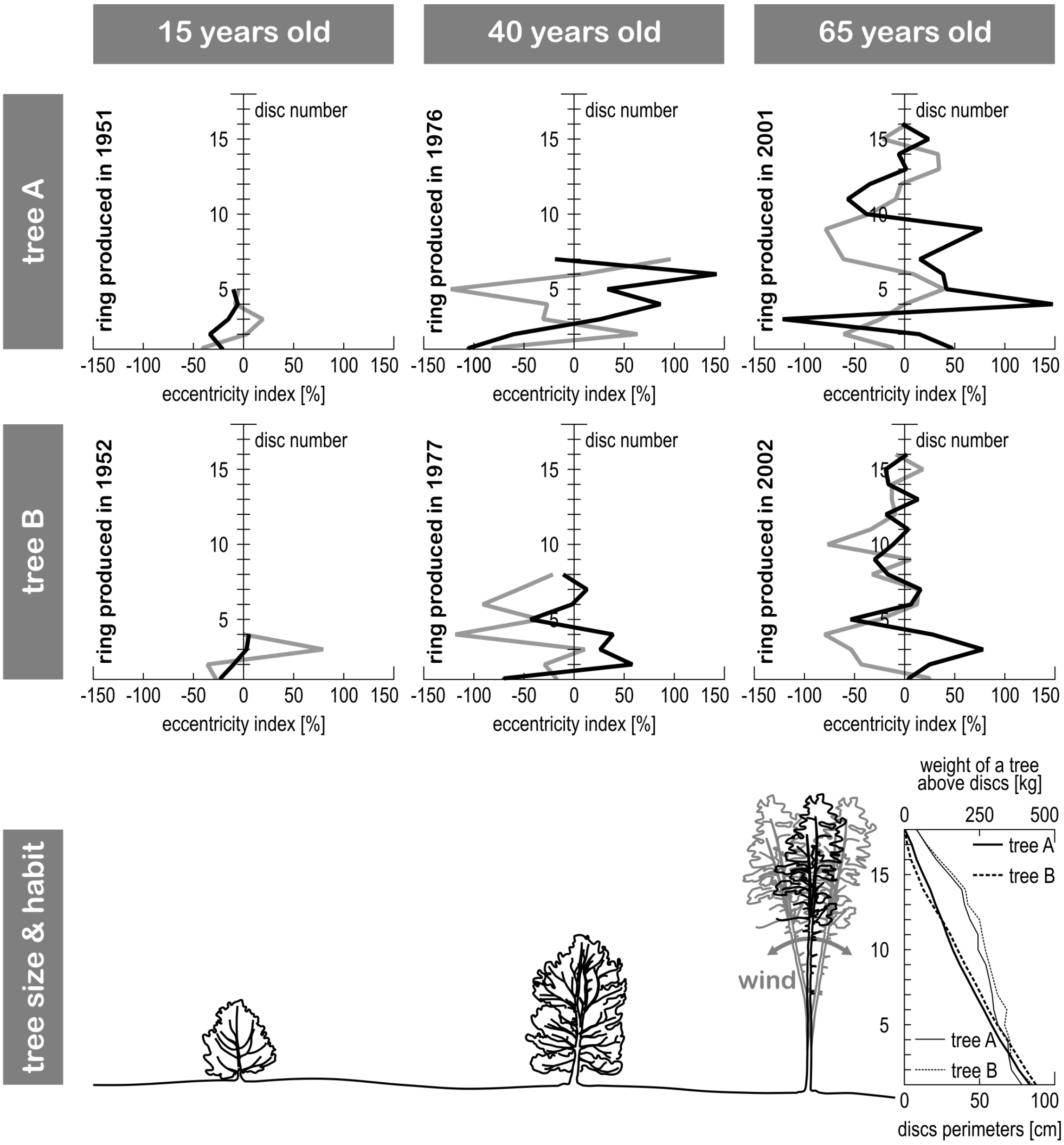

Figure 6: Vertical variability of eccentricity index values (black: W-E axis, grey: S-N axis) in young and mature pine trees (15, 40 and 65 years old) compared with tree size and habit.

The described situation is an effect of a tree's struggle to maintain balance and quasi-vertical position of its stem. In case of the occurrence of mechanical strains (e.g. due to tilting by wind gusts) in some parts of stem, these stem sections are a subject of more intensive radial growth at the compressed side (which is typical for coniferous trees, Scots pines among them). Uneven growth in one stem section is compensated through developing opposite eccentricity in stem sections right above and below. This alternating tendency of eccentricity development is transmitted along a stem and with increasing distance from the source (stem section where strongest strains occurred) it declines (e.g. W-E axis in tree B at the age of 65). The alternating direction of eccentricity in stems of studied trees serves to maintain straight vertical stems and is a reason of the previously described low correlations between sequences of eccentricity index from consecutive discs (Fig. 5).

We compared values, variability and amplitude of the vertical variation of eccentricity index in three selected age ranges. The youngest, 15 years old trees have the lowest level of eccentricity (index values range between -50 and 50%, Fig. 6). It is probably an effect of small size of young trees. Their height, determined using the number of tree rings in consecutive discs, did not exceed 4.5-

5.5 m. Stem perimeters, determined on the base of tree-ring measurements in lowest discs (0.5 m above ground level) were 6.7 cm (tree A) and 3.9 cm (tree B). Young trees resulted to be rather low and had small weight, so that not enough stress is generated to develop strong eccentricity.

In the middle age range (40 years old trees) values of eccentricity index are more extreme (e.g. from -122% to 148% in tree A, Fig. 6). This is an effect of increased size of a tree, which generated higher mechanical strains (their heights were less than 7.5-8.5 m, perimeters were: 10.9 cm – tree A, 9.6 cm – tree B). At the same time there is no clear tendency of vertical variation of eccentricity index. Vertical changes are abrupt and chaotic. This may be a result of Scots pine habit at the age of 40, when there is still a lack of one dominant shoot and branches grow along the whole stem length (Fig. 6). Each of the branches during wind can be a separate source of strains and stresses affecting the whole tree which is recorded in high level of eccentricity index along the whole stem.

In the case of oldest age (65 years old) there is a clear tendency to decrease the level of eccentricity along the stem from the ground up to the crown. It is probably connected with the decreasing weight of stem and branches lying above each consecutive disc (Fig. 6). Due to that, when we move from the ground level upwards strains decrease within the stem. In both trees there is also a clear increase of eccentricity at the height 1.5-3.5 m, 5.5-7.5 (tree A: 9-7 m and 5-3 m below the crown base) and 2.5-4.5 m (tree B: 7-5 m below the crown base). This seems to be connected with the way in which mature pine trees are tilted from one side to another by wind. Lower parts of stems (below c. 2 m above the ground) are the thickest, stiffest and stabilized by root systems buried in soil so they are more stable and do not deform due to wind. Higher parts of stems are tilted by wind tossing tree crowns, and this is the zone where particularly strong strains occur. Extremely strong eccentricity is developed there due to relatively large weight of above parts of tree and due to strong mechanical deformations caused by winds. On the other hand, top parts of stems develop weak eccentricity, despite strong wind impact. The reason is relatively small weight of above parts of tree generating weak strains.

Conclusions

1. Vertical variability of eccentric growth records the struggle of a pine tree to maintain vertical, balanced position (eccentric growth in one cross section is counterbalanced by opposite eccentric growth above and below).
2. Level of eccentricity in a mature 65 years old pine tree is controlled by: weight of above section of a tree, stem resilience and impact of stable root system. It varies along tree stem and is strongest at the height of c. 2-5 m above ground level, where heavy wing impact overlap with large weight of above parts of trees generating high strains.
3. Level of eccentricity in a 40 years old pine tree is high and controlled by tree habit (crown shape).
4. Level of eccentricity in a young 15 years old pine tree is low and controlled by small size and weight of specimens.
5. Eccentricity is a good sensor of inner strains within a stem and its vertical variability.

Acknowledgements

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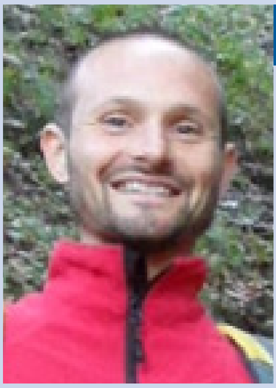

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