



TRACE 2023

8-13 May, Coimbra, Portugal

Book of Abstracts



WELCOME

Welcome to TRACE 2023, held in the University of Coimbra, Portugal, and organized by the Dendrochronological lab, MedDendro. The MedDendro lab was founded in 2005, a baby compared with the age of the University of Coimbra, founded in 1290. The MedDendro lab has several research lines, from studying the climate-growth relations of Mediterranean tree species, to the ecological meaning of intra-annual density fluctuations, xylogensis of conifers, impact of drought on the physiology and growth of trees, and more recently, on archaeological and historical woods.

Associated with the celebration of the 250 years of the Botanical Garden of the University of Coimbra, the MedDendro lab prepared an exhibition about wood anatomy, called INSIDE OUT, that you can visit during the TRACE conference.

Ana Carvalho
Cristina Marques
Cristina Nabais
Filipe Campelo
Mikael Moura

SCIENTIFIC PROGRAM

TRACE 2023 has 8 thematic sessions, Climate Reconstruction, Climate Change, Ecology, Forest Health, Wood Anatomy and Cambial Dynamics, Historical and Fossil Wood, Methods Development and Blue Intensity.

TRACE 2023 has six workshops before the start of the conference:

- *Introducing TreeRingJ: A tool to measure and record tree rings based on the free image-analysis platform ImageJ*, organized by Ignacio García González, University of Santiago de Compostela, Spain
- *Sampling roofs: an exchange of sampling procedures and protocols*, organized by Kristof Haneca, Flanders Heritage Agency, Belgium
- *Identifying wood*, organized by Alan Crivellaro, Forest Biometrics Laboratory, Faculty of Forestry, "Stefan cel Mare" University of Suceava, Romania
- *Tools and techniques for analysis of xylogenesis and wood anatomical data*, organized by Emanuele Ziaco and Eburne Martinez del Castillo, University of Mainz, Germany
- *Design and Deliver Effective Scientific Presentations*, organized by Alan Crivellaro, www.presenting-scientist.com
- *Tree-ring analysis using X-ray CT: theory, practice and hands-on visualization and analysis*, organized by Jan Van den Bulcke and Tom De Mil, University of Ghent and University of Liège, Belgium

The scientific committee wish you a nice TRACE Conference. Enjoy!

Aoife Daly, University of Copenhagen, DK
Cristina Nabais, University of Coimbra, PT
Emilia Gutierrez, University of Barcelona, SP
Filipe Campelo, University of Coimbra, PT
Ignacio García-González, University of Santiago de Compostela, SP
Jésus Julio Camarero, CSIC, SP
Joana Vieira, ForestWISE, PT
Paolo Cherubini, WSL, CH
Tomasz Wazny, Nicolaus Copernicus University, PL
Ulf Büntgen, University of Cambridge, UK
Ute Sass-Klaassen, University of Wageningen, NL

Conference Program – Oral Sessions

10th May, Oral sessions

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* Professional or student

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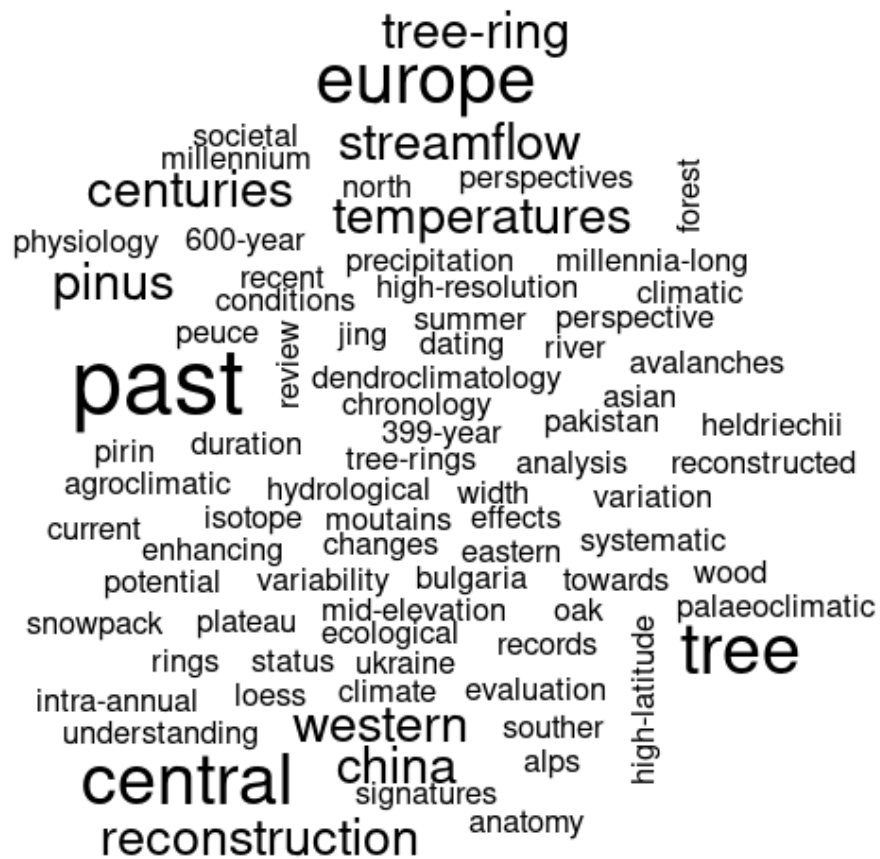
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Climate Reconstruction Session

Moderator

Jan Esper, Gutenberg University, Mainz, Germany



Evaluation of the current status of precipitation in North China over the past two centuries from tree rings

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The climate aridity since the mid-20th century has raised concerns about water resources on the Chinese Loess Plateau (CLP). A lack of extended observation-like precipitation records for the eastern CLP (ECLP) means that it remains unclear whether or not the current arid state of the CLP is unprecedented, and the spatial-temporal characteristics of hydroclimatic variability across the CLP over past centuries are not well understood. Here we present a regional hydrological-year precipitation reconstruction for the Heichashan Mountains, which successfully captures hydroclimate changes on the ECLP since 1773 CE. The reconstruction explains 48.72 % of the observed variance for 1957–2019 CE and reveals a wetting trend since the early 2000s and shows 2014–2020 CE to have been the second wettest period over the past 248 years. 1910–1932 CE was the longest and driest period over the past centuries. Furthermore, the 19th century was relatively wet, whereas the 20th century was dry. We demonstrate that droughts tend to occur in warm periods. Combining our new reconstruction with previously published hydroclimatic reconstructions, we find that hydroclimate has changed synchronously on the ECLP and the western CLP (WCLP) for most of the past two centuries. Some regional differences do exist, for example in the 1890s–1920s, when aridity gradually intensified across the ECLP, no similar drying is evident in records for the WCLP, although the 1920s megadrought occurred in both the ECLP and WCLP. Another difference is in the onset of the 20th-century aridity, which began in the 1950s on the ECLP, around 20 years later than it began on the WCLP. In addition to the known influences of the Asian Summer Monsoon and related large-scale circulations, this work highlights a major finding that the 1920s megadrought may be related to a regime shift in Northern Hemisphere temperature.

A 600-year snowpack duration reconstruction for the souther Alps

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Snow is an important component of the environment and climate of mountain regions, but providing a long-term historical context for recent changes is challenging, especially in areas where water availability or soil temperature is not a limiting factor for tree growth. Instrumental records certified that the Alps experienced a reduction of 5.6% per decade in snow cover duration in the last fifty years; this reduction has already significant effects in a region where economy and culture revolve around winter. However, despite the long tradition in weather record collection within the region, local measurements of snowpack often extend back only a few decades. As short-term series of observations are not adequate to describe snowpack dynamics and the full amplitude of mountain wintertime conditions, the absence of any continuous long-term (centennial or more) instrumental or reconstructed record of snowpack duration for the Alps so far, prevents it being correctly placed in the right context and assessing the true nature of the present-day shrinking. Here, we present a dendrochronological reconstruction based on a degree day model built to extract snow persistence from daily temperature and precipitation records, coupled with 572 ring-width series extracted from a prostrate shrub (common juniper – *Juniperus communis* L.) growing at high-elevation. Despite the typical slow and irregular juniper growth with the frequent presence of erratic cambial activity and missing rings, not always associated with disturbances or extreme climatic events, calibration/verification of ring width with a modelled snowpack duration series was remarkably strong and stable (medians of bootstrap calibration/verification statistics are -0.688 and -0.687 , respectively). We show that the current snowpack waning, estimated at more than one month (36 days) with respect to the long-term mean value, is unprecedented in the last 6 centuries. These findings, highlighting a record-breaking reduction in snow amount and duration on the southern Alps, stress the challenges ahead and the urgent need to develop adaptation strategies for some of the most sensitive environmental and socio-economic sectors.

Records of past temperatures in wood anatomy of high-latitude trees

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Temperatures in the North American Arctic are among the fastest rising in the world and are expected to increase at more than double the rate of global mean temperature change over the next century. The Arctic also experiences large summer temperature anomalies following explosive volcanic eruptions and is affected by large-scale modes of climate variability. It is therefore a critical region for observing and understanding both forced and internal climate system variability and feedbacks on the global climate system. The short length of instrumental and satellite observations, however, provides limited opportunities to observe the climate system. Here we present an updated tree-ring chronology from Firth River, Alaska (68.67°N, 141.02°W) to better understand climate variability and change in this region. In addition to the ring width chronology, which shows limited and unstable associations with climate, we create chronologies of wood anatomical properties that have been shown to contain a stronger climate signal. A preliminary maximum cell wall thickness (CWT) chronology from 3 tree series correlates significantly and positively with August minimum temperature during the period 1908-2010 CE. Our results show the benefit of using quantitative wood anatomy for the development of chronologies even with limited sample depth.

Central Europe summer temperatures over the past Millennium

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Europe experienced an unusually high frequency and intensity of summer heat waves during the last decade, which had strong impacts on ecosystems and society, and are likely to increase under projected global warming. A better understanding of pre-industrial temperature changes is needed to contextualize the recent anthropogenic trends and extremes. Here, we introduce 328 larch (*Larix decidua* Mill.) tree-ring samples from the Swiss Alps to develop a robust maximum latewood density (MXD) chronology back to 802 CE. A machine learning base provenance model was applied to identify temperature sensitive samples from historical buildings located above 1900 m asl to extend the modern part of the chronology back into medieval times. This approach enabled us to mitigate effects of elevational offsets among historical tree-ring series and to enhance the climate sensitivity of the resulting chronology. Cyclic growth reductions caused by larch budmoth (*Zeiraphera griseana*) outbreaks were detected and corrected by the impulse indicator saturation method. Highest correlation coefficients for our final MXD chronology were found with average June–August maximum temperatures over much of Central Europe and the Western Mediterranean ($r = 0.81$; 1901–2017). The spatial extent of the pristine temperature signal and the total period covered allow continuous investigations into the entanglements of climate and society over the past 1200 years.

Recent anthropogenic curtailing of Yellow River runoff and sediment load is unprecedented over the past 500 years

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The Yellow River (YR) is the fifth-longest and the most sediment-laden river in the world. Frequent historical YR flooding events, however, have resulted in tremendous loss of life and property, whereas in recent decades YR runoff and sediment load have fallen sharply. To put these recent changes in a longer-term context, we reconstructed natural runoff for the middle reach of the YR back to 1492 CE using a network of 31 moisture-sensitive tree-ring width chronologies. Prior to anthropogenic interference that started in the 1960s, the lowest natural runoff over the past 500 y occurred during 1926 to 1932 CE, a drought period that can serve as a benchmark for future planning of YR water allocation. Since the late 1980s, the low observed YR runoff has exceeded the natural range of runoff variability, a consequence of the combination of decreasing precipitation and increasing water consumption by direct and indirect human activities, particularly agricultural irrigation. This reduced runoff has resulted in an estimated 58% reduction of the sediment load in the upper reach of the YR and 29% reduction in the middle reach.

Intra-annual isotope signatures in tree-rings for high-resolution climate and physiology reconstruction – A Systematic Review

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Intra-annual tree-ring sampling techniques emerged in the 1970s as a promising approach to access information about environment and tree physiology at high-resolution time scale, from few days to weeks. Climate conditions vary within the growing season period, so that intra-annual sampling becomes relevant to dendrochronology and its applications related to global environmental changes. Isotope signatures in tree rings depends on the climate conditions and physiological mechanisms associated with the isotopic fractionation. Stable isotopes can be analyzed in small amounts of sample, so they attend to the requirements to be a suitable parameter for the sub seasonal approach. The intra-seasonal stable isotope strategy has been applied in dendrochronology research for about five decades, but it is still unclear if this technique fulfills the promise of being an innovative method to reconstruct climate and tree physiology at high-resolution time scale. To assess the advances achieved by this approach and propose new avenues for applications to support future studies, we systematically reviewed the scientific literature that relied on intra-annual stable isotopes. We obtained a total of 134 papers that cover study sites in six continents from which the United States, China, France and Italy have the highest number of studies. Carbon and oxygen stable isotopes were the most commonly analyzed in 99 and 73 studies respectively, while deuterium was analyzed by only six studies. Carbon and oxygen were analyzed together in 38 studies, and the three isotopes were analyzed together in three studies. All the surveyed papers were grouped in three different sets of applications, namely Dendroclimatology, Dendroecophysiology and Methodological Advances. The longest intra-ring series reached 460 years and the highest-resolution intra-annual sample had 186 measurements per ring, both for dendroclimatological applications. In addition, we collected information of which environmental and physiological factors influenced intra-ring isotope signatures. Temperature, precipitation, relative humidity and source water were the most commonly climatic influences. Stomatal conductance, photosynthetic rate and reserve mobilization were the most commonly physiological influences in the intra-annual isotope signatures. Furthermore, studies reveal the rise in accuracy of climate and physiology reconstructions when two or more isotopes are combined. Thus, this systematic review points to a significant progress in all three categories of applications for dendrochronological studies, but there is still room for further advances in intra-annual stable isotope analyses.

Towards an enhancing of our understanding of climatic variability in Eastern Europe

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Despite the existence of multiple proxy-based climate reconstructions and relatively long instrumental records throughout Europe, certain regions still lack reliable information about past climate, particularly in the eastern parts of the continent. The presence of limitations in data quality and significant uncertainties in existing records is the underlying cause of this issue. As a solution, we are developing a set of temperature reconstructions across the Carpathian Mountain arc, which will enhance our understanding of recent climatic variability in this region. This effort involves the development of annually resolved, robust, and high-quality summer temperature reconstructions covering the past 300-400 years for four locations across the Carpathians, including N Romania, Slovakia, Ukraine, and S Romania. These temperature reconstructions are being based on chronologies of tree-ring width (RW) corrected for disturbance, Blue Intensity (BI) and color bias-free surface intensity (SIB) from scanned and microscope-based high-resolution images, as well as traditional and surface-based quantitative wood anatomy (QWA/sQWA). We have developed and assessed preliminary versions of the multi-parameter temperature reconstructions based on ~18,000 tree ring width (RW) and ~1000 Blue Intensity (BI) series from samples of living Norway Spruce (*Picea abies*) from the upper tree line throughout the four aforementioned Carpathian locations. We conducted a Principal Component Analysis (PCA) to identify the primary forcing in the variation of tree growth in the Carpathians as a whole and the mean temperature anomalies were reconstructed using principal component regression. Our preliminary temperature reconstructions, utilizing the RW and BI datasets, demonstrate that up to 56% of their variability can be explained by April-September temperatures. Although BI responds strongly to this broader seasonal window, the RW response is also significant but generally weaker and mostly restricted to a narrower (June-July) season. We performed an initial detailed evaluation over the AD 1901-2010 period overlapping with the instrumental temperature dataset (i.e., the full calibration period) and evaluation of the full length of the Carpathian-wide and sub-regional reconstructions is ongoing. The initial proxy results, validated by meteorological

station data, indicate a clear increasing temperature trend since 1980 in all four regions, which is also evident in other European high-elevation sites, such as the Alps, and demonstrates clear regionality. Moreover, wavelet analysis of PC1+PC2 timeseries reveals a strong multi-annual periodicity (2-7 years) in the early 20th century (~1910) and between 1930 and 1940. However, after 1950, a dominant and continuous multidecadal periodicity (~20 years) is observed in our data. We expect that the combination of all available parameters will further strengthen the climate signal, providing records with reduced uncertainty that will help further explore the paleoclimate of the Carpathians. Incorporating novel data from underexplored regions using tree-ring based climate reconstructions is a crucial advancement in enhancing our comprehension of the climatic dynamics at a European regional-scale.

Dating of avalanches in Pirin Mountains in Bulgaria by tree-ring analysis of *Pinus peuce* and *Pinus heldreichii* trees

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Pinus peuce and *Pinus heldreichii* are two species famous for their longevity and very limited distribution. They are found only on the Balkan Peninsula and small area in southern Italy (*P. heldreichii*). Pirin Mountains in Bulgaria are the refuge of some of the best-protected forests of those species in the world. Due to the steep and long mountain slopes the forests are affected by avalanches and some of the trees keep record of past avalanche activity in their tree rings.

We selected as study area the Bunderitsa valley, which is famous as access point for the highest peaks in the mountains and after the construction of Bansko ski resort has become even more important for winter tourism. After initial mapping of the area prone to high avalanche activity with the use of satellite images and historical aero photos we collected tree-ring cores from affected trees on the borders between the forests and some of the large avalanche couloirs. Our findings showed that avalanches are the main factor shaping the structure of the forests in the valley. Fires played high role in the past, but have not occurred in the last decades. Past avalanche activity has opened long-lasting avalanche tracks in the forests and more than 56% of the potential forest area is strongly affected by them. The trees which were hit by avalanches had different types of damages. Most of them were with broken stems. Frequently the trees were tilted and, in some cases, we found partially uprooted trees, which had high inclination of the stems, but were still living. The most frequent types of tree-ring responses were: 1) sharp growth suppressions with sequences of very narrow and sometimes missing tree rings; 2) sequences of tree rings with reaction wood; 3) tree rings with resin spills; and 4) wounds followed by missing tree rings and callus tissue covering the wounds. Lines of traumatic resin ducts were rare in the studied species. The dating of avalanches often required several tree-ring cores from one tree.

By use of tree-ring analysis we reconstructed past avalanches that affected certain areas of the study region. The big couloirs were affected by smaller avalanches annually, while bigger avalanches have hit the neighbouring forests almost every decade. While in some years there were large avalanches in all studied couloirs (e.g. 1996, 1987, 1963, 1957), other big avalanches affected only specific areas. The oldest dated events were in the 1720-s (Palashica slope) and 1830-s (Todorka slope).

Our findings demonstrate that avalanches in the valley are of high importance and require more attention by authorities both as risk factor for human health and life and as natural disturbance shaping the forest structure and dynamics.

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Palaeoclimatic potential of the recent oak tree-ring width chronology from western Ukraine

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Despite the recent effort to compile long oak chronologies in Eastern Europe, more investigation into their spatio-temporal climate signals is essential to better understand their applicability for palaeoclimatic analysis and dendrochronological dating.

In this study, we investigate the climate sensitivity of the recent oak tree-ring width chronology of Transcarpathian Ukraine and its coherence with 31 oak chronologies from Ciscarpathia Ukraine, Slovakia, Romania and Hungary. The new chronology consists of 247 samples of living trees from 13 sites between 140 and 600 m.a.s.l. and span period 1836–2020 (185 years, common period 1918–2009). Precipitation and, even more prominently, the SPEI drought index during the growing season were found as the main driver of oak growth on the border of the Carpathians and the north-eastern Pannonian Basin. Also spatial correlations of the chronology show particularly high explained variability of the 3-month SPEI during May–August in the year of tree-ring formation roughly between 18.5–29°E and 45–52°N.

Furthermore, we found a high correlation among tree-ring chronologies from Transcarpathian Ukraine, eastern Slovakia and north-western Romania, which indicates good spatial potential for dendroarchaeological dating in this area. Further extension of oak recent chronology by historical TRW series will enable accurate dating of historical constructions and climate reconstruction in the region of Western Ukraine.

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Millennia-long perspectives on agroclimatic conditions in central Europe

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Central Europe has experienced severe droughts in recent years, with considerable impacts on the agricultural sector. Placing these events in context of natural climate variability is, however, constrained by the limited observational record. Here, we use tree-ring stable oxygen and carbon isotopes to develop annually resolved reconstructions of growing season temperature and summer moisture variability for central Europe during the past 2,000 years. The reconstructions are interpolated across the region to produce spatial estimates of the optimum yield crop, based on modern references of climatic forcing. Historical documentation of agricultural productivity and climate variability since 1090 CE provides strong quantitative verification of our new reconstructions. The records capture known extreme climatic events, such as the Medieval (920-1000 CE) and Renaissance (early 16th century) droughts, but also suggest alternative interpretations of the relative influence of temperature and moisture on agricultural drought during the first millennium. We suggest that Czech agricultural production has experienced significant extremes over the past 2,000 years, including periods for which there are no modern analogues.

Reconstructed Jing River streamflow from western China: a 399-year perspective for hydrological changes in the Loess Plateau

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The Jing River is a secondary tributary of the Yellow River located in the middle of the Loess Plateau of China, where severe water scarcity and soil erosion have threatened sustainable social and economic development. Understanding the historical hydrological climate change can better assess and solve water resources problems. Accordingly, we used five machine learning models (MLM) and simple linear regression (SLR) based on tree ring width to reconstruct the January-June streamflow of the Jing River. The reconstruction advantage and streamflow variation information exhibited by single model are not sufficient. Consequently, the six models were constructed to a new ensemble streamflow reconstruction. During the past nearly four centuries, the Jing River has experienced seven wet periods and ten dry periods, and drought events recorded in historical literature are included. The main atmospheric forcing factors driving the streamflow variability are the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO), which regulate the climate and hydrology by affecting water vapor fluxes and the Asian monsoon. Comparison with other regional reconstructions, our record reveals a decrease in the probability of extreme streamflow events after 1850 under the influence of human activities and global warming. The different future climate scenarios indicate that if temperatures continue to increase, the streamflow of the Jing River will decrease substantially, and the conditions of water resources will continue to deteriorate. This new streamflow reconstruction can be used as a reference to analyze regional hydrological and provide a basis for water resource management and policy formulations.

Intra-annual growth dynamics to global change of *Pinus sylvestris* and *Quercus pyrenaica* mixed forests in central Spain during the last decade

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The Mediterranean region is one of the most sensitive hot spots on the planet in terms of the effects of climate change, since it is located in an intermediate zone between the temperate climate of central Europe and the arid climate of North Africa. For the past decades, anthropogenic climate has negatively impacted forests productivity across this region, especially in drought-prone areas. In this future article presented in a poster, our main aim is to study the cambial phenology and kinetics of two of the most important Mediterranean species, *Pinus sylvestris* L. and *Quercus pyrenaica* Willd., at their elevational transition ecotone in the Center of the Iberian Peninsula.

Using bi-weekly microcore samplings along with daily climatic data available from nearby meteorological stations, we studied the xylogenesis and cambial phenology of 6 trees (different every year) of each species over the last decade. Most recent studies on xylogenesis typically rely on 1-3 years of samplings, since collecting and processing microcore samples is a time-consuming process; however, we monitored the wood formation process for more than 10 years from mid-March to late November, thus counting with a longer time window to dive into each species intra-annual growth dynamics to global change with great level of detail. We also find especially promising carrying out detailed analyses of tree cambial phenology and kinetics during the most extreme climatic years over the last decade.

Previous studies in this area forecast a reduction in *Pinus sylvestris* distribution range in favour of more drought-tolerant species, such as *Quercus pyrenaica*. Species adjust their phenology to climate change by shifting or compressing growth and reproduction seasons according to specific regional environmental drivers (besides local adaptations and/or individual plasticity to climate). Thus, we expect to find inter-annual differences among the species performance in relation to climatic constraints throughout the last decade.

Some of our main hypothesis to be tested during the forthcoming months are: (1) Temperature and photoperiod both play important roles in annual resumption of cambial activity for the two species; (2) Previous winter temperatures might have a legacy effect on spring growth reactivation of the upcoming year, expanding or reducing the duration of the growth season; (3) Spring rainfall, and particularly VPD, play as well an important role in the

growth process, especially during the early stages of xylogenesis (enlarging phase); (4) We expect to find differences between *P. sylvestris* and *Q. pyrenaica* cambial phenology and kinetics in terms of their response to climatic constrains; (5) Water deficit experimented by trees during the driest years should translate into a shortening of the growing season and decreased growth rates.

Identifying deviant population responses across Europe from public repository data

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Growth responses in trees are a function of environment and genetically informed responses to the experienced environment. Under climate change, there is a strong need to identify adaptive genetic variation for continued healthy forests. Here, we use mixed effects regression approaches using ITRDB tree-ring measurements from over 300 studies and publicly available historical weather data to understand patterns of stand-level deviation from expected regional climate responses across Europe. We focus on Norway Spruce (*Picea abies*) because of its large environmental range, moderate genetic differentiation between populations and ubiquity in tree-ring studies.

Spatiotemporal changes in drought sensitivity captured by multiple tree-ring parameters of Central European conifers

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Global environmental changes have increased the frequency and intensity of climatic extremes, particularly heatwaves in tandem with severe droughts (i.e., hotter droughts), which can significantly affect inter-annual tree growth patterns and leave multi-year lags in growth recovery (i.e., drought legacy effects). Intensifying climatic conditions carry major consequences for contemporary forest dynamics and future ecosystem functioning, but the effects of recurrent severe climatic events on tree growth are inhomogeneous across individual species' natural distribution ranges due to the large spatial heterogeneity within a broad set of environmental conditions. Despite numerous studies quantifying the impacts of regional drought effects ranging from tree to ecosystem scale, uncertainties still remain regarding the mechanistic basis of drought legacy effects in conifer wood formation, as well as individual species' ability to cope with the rising year-to-year climatic variability across the Central European natural forest landscapes.

In order to evaluate the general climate-growth interactions and assess species- and site-specific tree growth response to severe droughts, we used multiple tree-ring parameters (i.e., tree-ring width and blue intensity parameters) from an extensive tree-ring dataset with > 1000 series from 23 nature forest reserves across an altitudinal range in Czechia and Slovakia. These forests represent a wide range of environmental conditions of naturally developing Norway spruce and Scots pine, making them ideal for inferring general conclusions on the effects of intensifying climatic conditions on Central European forest dynamics.

We combined linear correlation analysis of tree growth with average climate (i.e., mean temperature, precipitation totals, and moisture index) and during extreme drought years, with forward (non-linear) modelling of tree growth over the period 1950 - 2018. Overall, we observed a large spatiotemporal variability in growth response to summer season temperature and moisture availability across species and parameters, but with the general trend of increasing moisture-growth sensitivity in recent decades across the Scots pine mountain forests and in both species' lowland sites. Furthermore, both species demonstrated temporally unstable and nonlinear relationships with the dominant climatic controls over the

20th century. The VS-lite model captured the non-stationarity in climate-growth relationships generally well and accurately estimated high-frequency growth variability in recent decades, indicating a strong coincidence of regional drought events with tree growth reductions. Growth reductions during extreme drought years and discrete legacy effects identified in individual wood components were most pronounced in trees developing at low elevation dry sites, and together with the observed declining growth trends in recent decades, suggest an increasing vulnerability of Norway spruce and Scots pine on Central European xeric sites under intensifying climatic constraints.

The role of contemporary climate changes in the shaping of growth response and stability of spruce ecosystems in the Western Sudetes

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Forest ecosystems of the Western Sudetes (South-West of Poland) have undergone enormous transformations under the influence of anthropogenic factors over the past several hundred years. In the lower subalpine forest zone, primeval forests were cut down in the 17th and 18th centuries and replaced with spruce monocultures. The distortion of forest ecosystems, reducing the species richness, led to the disturbance of the stability and regression of forests over a large area. It was revealed in a particular way during the ecological disaster caused by "acid deposition", the efficiency of which in the Western Sudetes reached levels not found anywhere else in the world. Between 1980 and 1990, deforestation and areas affected by severe negative changes covered more than 50% of forest areas in this region. The remedial action taken, e.g. the reduction of industrial emission and the redefining of the spruce monocultures in terms of species and structure yielded quick results and improved the condition of ecosystems. Finally, the last three decades of instrumental measurements clearly document the progressing process of global warming. In the mountainous regions of central Europe, the following phenomena can be observed: unprecedented scale of warming, a downward trend in precipitation totals in spring, decreasing snowiness of winters and constantly growing threat of drought.

In this context, spruce ecosystems of the Western Sudetes constitute an extremely interesting and unique area of study, characterized by an exceptionally intensive role of anthropopressure together with a rich history of exploitation and reconstruction of tree stands. The main task that the authors of the project set themselves is not only to describe the impact of climate change on the stability of spruce ecosystems as a whole. Their primary objective is to highlight the differences in incremental response separately: in natural stands, monoculture stands of foreign origin and in stands with various degrees of degradation in the period of the ecological disaster. All this contributes to a very strong spatial differentiation of habitat types between zones: (1) up to 500 m a.s.l. (dominated by deciduous and mixed tree stands; outside the area of exceedance of acid critical loads), (2) altitudes of 500-950 m a.s.l. (lower subalpine forest; low to medium of exceedance of acid critical loads; dead tree trunks below 10%), (3) zone of upper subalpine spruce forests (high and very high exceedance of acid critical loads; comprises 50% dead tree trunks).

All 166 core samples used in the present study were collected between May and October 2022 in 16 locations, divided into 3 groups as described above. In each location between 16 and 29 samples of cores were collected. Measured values were transformed with the standard procedure: the trend line was removed in the Arstan program and the chronology was based on the autoregressive modelling calculating the chronology with the least square method. Further cross-dating was computed in the COFECHA program and also used for the detection of the missing and false annual ring. Spruce trees were also sampled using the Trephor tool at two-week intervals to obtain the micro-cores containing cambium, and secondary xylem and phloem differentiated in 2022 year.

Preliminary measurements showed that a progressing rise in air temperature contributes to improving the condition of forest ecosystems in the upper montane, in particular in the tree-line zone, where a slow spruce expansion occurs. For the vegetation period the width of annual growth rings is directly proportional to the temperature and inversely proportional to precipitation. These dependencies are reversed in the lower parts and in the foothills. Therefore, the rising temperature is responsible for the fact that thermal conditions in the lowest parts of the mountains are not optimal for the development of spruce, and in the abnormally warm and dry years even oppressive.

A multimodel approach exposed an enhanced beech growth in European mountains under climate change scenarios

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Productivity of forest trees is predicted to change in response to forecasted changes in climate. Empirical modelling techniques are frequently used to (i) explore the sensitivity of tree growth to environmental variables, and (ii) predict the future growth of trees and forest stands under climate change scenarios. However, the modelling approaches have a crucial influence on

predictions of the sensitivity of trees to environmental factors. Here, we used a network of 70 plots established across European mountain beech forests via the COST Action CA15226 initiative and tree-ring width (TRW) data from 1630 beech trees to test various modelling approaches to build empirical predictive growth models. We used a sensitivity analysis to explore the “sensitivity” of beech tree growth to various climate and soil variables across Europe and to compare different ways to build empirical models. Results revealed similar prediction errors (RMSE) ranging between 3.71 and 7.54 cm² of basal area increment (BAI). The models explained most of the variability in BAI ranging from 54% to 87%. Selected explanatory variables (despite being statistically highly significant) and the pattern of the growth sensitivity differed between models substantially. We identified only five factors with a consistent effect (i.e., same effect and same sensitivity pattern) in all models: tree DBH, competition index, elevation, GINI index of DBH, and soil silt content. All empirical models indicated that beech growth declines with increasing elevation and silt content in the soils. However, the sensitivity to most of the climate variables was low and inconsistent among the models. The results also suggested that the more diversified the stand DBH structure the lower the mean tree growth. The empirical models suggest that beech in European mountains will, on average, likely experience better growth conditions under both 4.5 and 8.5 RCP scenarios.

How to improve the comprehension of climate change - an interdisciplinary approach.

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In the week from 31st May to 06th June 2021, the large-scale weather patterns (GWL) over Central Europe changed from Anticyclonic North-Easterly (NEa) to High Scandinavia-Iceland (HNFa) and back to NEa, leading to rainfall events in the province of Bavaria, Southeast Germany. A broad public could observe this event as a low-pressure area coming from the northwest in the daily weather forecast.

In general, however, particular GWLs affect different regions over Bavaria differently, since precipitation amounts and duration, and temperatures vary depending on the topographical situation and geographical location. Consequently, the physiological response of trees also varied specifically to local site conditions in early June 2021, as determined with dendrometer measurements throughout Bavaria.

This tree monitoring was conducted within the BayTreeNet project and included tree diameter and sap flow measurements on 11 individual trees, recorded every 20 minutes and displayed in real-time as graphs on the project homepage (<https://baytreenet.de/>). Partner school classes assessed these tree responses and interpreted them with the help of climate data that are also displayed on the website. By linking the tree responses to the prevailing local weather conditions and the causing GWLs, students described and communicated the particular physiological status of a tree in a specific region. During teaching units, the students verbalized the results in short texts and published them via Twitter to reach a large number of followers.

With this example of a one-week monitoring period in early summer 2021, we will synthesize this multidisciplinary approach combining climate dynamics, forest health, and educational science. We will further analyse the site-specific response of trees to specific weather patterns. Finally, the associated tweets show how high school students understand and grasp the forest-climate relationships.

Thus, in addition to the detailed investigation of physiological responses of trees and variations in the frequency and intensity of specific GWLs due to climate change, the transdisciplinary project aims to stimulate communication and education about the local effects of climate change on forest ecosystems in larger regions with a complex terrain structure.

The Interplay between Climate Change, Tree Defense, and Growth in *Picea abies*

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The ongoing environmental changes due to climatic and human activities are rapidly affecting various ecosystems, with trees being particularly vulnerable, especially those found in mountainous regions. To understand the ability of these trees to adapt and evolve in response to these changes, it is crucial to examine their physiological responses. This study aims to investigate the relationship between the climate variables of temperature, cloud cover, and Palmer Drought Severity Index (PDSI) and the physiological health and growth response of *Picea abies*, a tree species found in central European mountain forests.

To achieve this, we conduct a dendrochronological study in three forest sites, Šumava and Jeseníky in the Czech Republic and the Carpathians in Slovakia, from the REMOTE forest network. Tree growth is analyzed through the examination of ring-width series, and tree defense mechanisms are evaluated through the analysis of resin duct time series.

Our study aims to shed light on the complex interplay between climate change, tree defense mechanisms, and growth in *Picea abies*. We expect to find a positive relationship between the number of resin ducts and temperature, such that as temperatures increase, the number of resin ducts in the trees will also increase, resulting in improved growth. These findings will provide new insights into the adaptability of this species in response to changing environmental conditions and contribute to a better understanding of the physiological responses of trees to environmental changes as well as will inform sustainable forest management strategies in a changing climate.

Structural and Species Diversity Do Not Stabilize Forest Growth Under Climate Change Stress

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Tree growth is synchronizing worldwide. The pressure imposed by climate warming on xylogenesis pushes trees to grow under conditions limited by elevated temperatures, scarce precipitation, or both. The lengthen of this state through time might lead to a destabilization of the entire forest growth, likely more accused in mono-specific systems due to the shared responses of same species' trees to climatic elements. Accordingly, the stabilization should arise when homeostasis effects emerge in forest composed by diverse species whose growth responses to climate are disparate. Likewise, forest structural heterogeneity could also promote compensatory paths to favour ecosystem stability, since recent research have fixed it as a relevant mediator of forest productivity. However, while the relationship between climatic stress and synchrony is notorious, evidence for the existence of compensatory effects is scarce, if not lacking, when considering tree dominated ecosystems. In this work, we explore the relative role of three drivers of forest productivity —climatic variability, species diversity and size-structure diversity— to control forest growth stability through the asynchrony of individual tree's secondary growth. If compensation exists, a buffering effect of diversity should promote the tree growth asynchronization necessary to stabilize aggregated forest growth. To test this assumption, we collected dendrochronological samples in 18 secondary forest stands composed of 1 to 5 tree species in the Sierra de Gredos Mountain range (Central System range, Iberian Peninsula) and assessed Basal Area Increment (BAI) and historical Basal Area (BA). We used Structural Equation Modelling (SEM) to evaluate relevant paths and its relative weights on stabilizing and destabilizing dynamics over time. The fitted SEM accounted for the following variables: SPEI index as climatic element, Shannon species diversity index of trees' BA as species diversity, Gini index of trees' BA as structural heterogeneity, the proportion of non-significative relationships in a BAI correlation matrix as a measure of growth asynchrony, and the coefficient of variation of the stand mean tree growth as a proxy of aggregated forest growth stability; all of them computed over time windows of 1-year lag starting from 1980 to 2017. SEM was built with two linear mixed-effects models accounting for

temporal autocorrelation: equation (1) modelled the influence of climate, species diversity and structure heterogeneity on asynchrony and equation (2) modelled the influence of asynchrony on forest growth stability. The results revealed the significant dependence of asynchrony on climate, but not on both diversity proxies. Periods with negative SPEI values favoured tree growth synchronization ($R^2 = 0.09$). Besides, forest growth stabilized in accordance with asynchronization patterns ($R^2 = 0.21$). Goodness of fit in SEM was Fisher's $C = 9.007$ ($p = 0.173$). Our analysis highlights a thorough climate-driven destabilization of forest growth in the absence of diversity buffering dynamics. Assessing the conditions under which buffering effects arise must be critical, bearing in mind that the limiting effects of climate could produce unstable growth trends, making forests prone to adverse events as growth suppressions.

Growth trends of the main Central European tree species

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Climate change affects terrestrial ecosystems including Central European forests. Even though, changes in temperatures and precipitations are relatively slow and forest ecosystems show a high level of resistance, they may result in changing patterns of stem biomass allocation or dieback of specific tree species in certain regions. By analysing the growth trends the areas sensitive to forest dieback may be identify. To identify such areas, we used data available in the Czech national tree ring database (www.treedataclim.cz). Sites with complete record of tree-ring with data in the "recent" period 1990-2014 (almost 500 sites) were used for the analysis. To analyse growth trends we used basal area increment as it well represents stem biomass allocation. First, tree growth (basal area increment) was fitted with GAM, using cumulative basal area and tree age as predictors to filter out the age and size effects of each tree. Consequently, mean growth curve of the "mean tree" (median age and size calculated for each site and species) was established for each tree species per site. PCA analysis was then performed to identify growth trends of main tree species across entire dataset. First three axes explained 99.3 % of variability (90.2, 7.5 and 1.6 % respectively). Based on correlation with individual axes four main patterns of growth trends were identified. First two main trends, correlating with second axis, were strictly positive (47.0 % of sites) or strictly negative (21.6 % sites). The second two trends, best correlating with third axis, were characterized by switching trends at the beginning of the third millennia from positive to negative (10.6 % of sites) and from negative to positive (6.2 % of sites). Our results revealed strong differentiation in presence of trends due elevation among species. Except oak sites with strictly positive trend in lower elevations, and fir having almost uniformly positive growth trends in all elevations. The rate of sites with strictly positive growth trend increases with increasing elevation. Below 700 m a.s.l. growth trends of spruce, pine and beech are prevailingly negative, while sites at higher elevations exhibit mostly positive growth trends. Negative growth trends were characteristic for pine and beech stands and old stands, whereas positive growth trends were typical for sites

with low temperature and high precipitation. Based on our results, fir will profit most from the future climate conditions. In lower elevations then decline of beech, spruce and pine may be expected.

Growth projections of European beech reveal widespread decline until 2050

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A central challenge of global change research is the projection of the future behavior of a system based upon past observations. Here, we applied a linear mixed-effects modeling framework building on Cook's aggregate growth model, i) to capture variation in climate dependent productivity and ii) to project growth for the near-term (2021-2050) future across the entire distribution of Europe's most abundant broadleaved tree species European beech (*Fagus sylvatica*). Using a unique pan-European tree-ring network comprising 26,555 trees from 2,133 locations we modeled radial growth to annually varying climate as a function of mean climate conditions (mean annual temperature, mean annual precipitation, continentality via annual temperature range).

Over the calibration period (1952-2010) the model yielded appropriate regional explanatory power ($r=0.55-0.84$) across the entire range. Considering a moderate climate change scenario (CMIP6 SSP2-4.5, 10 models) beech growth is projected to decrease over the period 2021-2050 relative to the to the calibration period across most of its distribution, in Central and Western Europe by 5-15%, in the Mediterranean region by 10-25%. Interestingly, the Mediterranean region has a weaker model fit due to lower site replication, resulting in larger uncertainties of future growth projections. Beech forests growing historically (1951-1980) below a mean annual temperature of 6°C are projected to benefit from climate change. The model predicts a 3-23% growth increase in the high elevation clusters of the Alps and Carpathian Arc. However, these "winner" regions only comprise around 10% of beech's current occurrence.

Contrary to previous research we show little potential for growth increases at the northern range edge, i.e., radial growth is still primarily water limited in southern Scandinavia, reducing the potential to extend beech's distribution beyond its current range.

Predicted sea-ice loss affects Arctic driftwood supply

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Arctic driftwood was essential for the Norse expansion and its permanent settlements. Long-term changes in the transportation and accumulation of Arctic driftwood are, however, poorly understood. Here we use tree-ring measurements of 289 driftwood samples from an almost uninhabited part of north-eastern Iceland to reconstruct their age and origin. Based on 240 tree-ring chronologies from the Eurasian boreal forest, we show that the majority of pine and larch samples originated from the Yenisei catchment in central Siberia. An abrupt decline in the amount of driftwood along the Icelandic coastlines since the 1980s is corroborated by eyewitness reports of local farmers, and likely to exacerbate under predicted anthropogenic warming. Despite direct and indirect effects on changes in logging activity and ocean currents, warming-induced sea-ice loss is likely to terminate Iceland's driftwood supply by 2060 CE.

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White spruce under climate change - does winter-spring water availability become more important for earlywood cell dimensions at treeline as temperatures rise?

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Tree growth in cold environments is generally limited by temperature: thresholds regulate growth onset in spring, and summer temperatures control cell wall thickening and density of the latewood. However, little is known about how climate affects cell dimensions in the hydraulically relevant earlywood. This is particularly true for white spruce in northwest North America, for which few studies of wood anatomy exist, and which is strongly affected by climate change.

We studied four white spruce sites in the northern treeline ecotone from oceanic western Alaska to more continental western Canada. Using quantitative wood anatomy, we tested how time series of xylem anatomical traits, particularly earlywood lumen area (LA), but also earlywood cell wall thickness (CWT), are related to temperature and precipitation during a cooler (1950-1976) and a warmer (1977-recent) period.

Surprisingly, we found that earlywood LA was often negatively correlated with temperature around or just before the assumed timing of earlywood formation (May, June). This correlation was often new or stronger in the second, warmer period. At the same time, earlywood LA was positively related to precipitation in the previous winter (oceanic site, roughly January-April), spring (April-May) or current summer (continental site). Earlywood CWT often showed inverse correlations, but the strongest effects were generally found for temperature in the preceding summer.

Our results suggest a complex climatic control on earlywood formation of white spruce at our study sites, consisting mainly of (i) a prominent role of winter-spring water availability, possibly related to desiccation or drought around the timing of growth onset (LA) and (ii) memory effects of the previous year (CWT). As warming continues and winters/springs become drier, this could have considerable impacts on tree hydraulics and carbon sequestration.

Response of urban trees to extreme drought events

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Urban trees are renowned for their role in the green infrastructure to support life quality and well-being. But trees are only a reliable source of ecosystem services if they withstand the harsh environmental conditions found in the cities. Urban trees face higher temperatures and evaporative demands as an effect of the heat islands, as well as they may have restricted access to underground water for the extensive soil impermeabilization. These intrinsic characteristics of the cities make trees potentially vulnerable to extreme drought events. To assess the responses of urban trees to extreme drought events, we analyzed the intra-annual variation in carbon isotopes from *Tipuana tipu* (Leguminosae) trees sampled in the megacity of São Paulo, Brazil. We sampled increment cores of trees from a public park and street trees. We measured the stable carbon isotopes in ten segments of each tree ring from 2010 to 2016 to represent the beginning middle and end of the growing season, aiming at understanding the responses of these trees to the drought of 2013 and 2014. We also measured the tree-ring width to assess any change in growth rate. We used regression trees to analyze the variation in the values of the carbon isotopes in relation to site conditions, period during the growing season and the effect of drought. The results show that site conditions exert the strongest effect on carbon isotopes from the tree-rings of *Tipuana tipu* trees. Trees growing in the street display higher values of stable carbon isotopes compared to trees from the park. Among the street trees, the highest carbon isotope values were observed at the beginning and middle of the growing season during the drought years. On the other extreme, the lowest values of stable carbon isotopes have been observed in the trees from the park during wet years at the beginning and end of the growing season. Because carbon isotopes values increase with lower stomatal conductance and assimilation rate, as well as higher use of carbon reserves, these results show that trees growing in the streets need to keep their stomata closed for longer periods to cope with the more demanding environmental conditions. Trees from both sites likely reduced stomatal conductance and assimilation, and or used more carbon reserves, to cope with the drought of 2013 and 2014. The effects of the drought were stronger during the middle of the growing season in the park trees, and the beginning and end of the growing

season in the street trees. All these response mechanisms to this extreme drought event allowed tree from both sites to keep their growth with no significant change in growth rate compared to previous and following years. These results point to the resistance of *Tipuana tipu* trees to the effects of extreme drought events in urban areas.

An overview of extreme years in *Quercus* sp. tree-ring records from the northern Moldavian Plateau

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Given the economic and ecological importance of forestry, it is crucial to study the relationship between the variability of tree-ring width and extreme climatic events. In this study we made use of a regional oak tree-ring network from six stands that cover the northern Moldavian Plateau (eastern Europe), to present an overview of how tree-ring growth is affected by some climatic extreme events. Tree-ring parameters (earlywood tree-ring width, latewood tree-ring width, and total tree-ring width) of *Quercus* sp. were used to analyze the climate-growth relationship and explore the influence of extreme events on tree-ring growth. For this, we have selected the six most extreme positive and six negative years of tree-ring growth and addressed the seasonal cycle of tree growth in comparison with the main climatic parameters, and evaluated both immediate and lagged consequences of extreme climatic events on tree-ring growth as well their capacity to recover. Our results indicated the variation of oak tree-ring width from the Moldavian Plateau is mainly influenced by the long-term drought conditions, (Standardized Precipitation Evapotranspiration Index for June 12 months accumulation period), and two years in a row with drought conditions represent an important limiting growth factor for this specie.

Climate change in the Mediterranean region promotes formation of intra-annual density fluctuations in *Pinus pinaster* Aiton influencing its growth and water use dynamics

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In recent decades, forests around the world are facing the effects of progressive climate change. The Mediterranean basin is one of the most affected areas: in this region extreme events, such as drought and heat waves are increasing, with serious consequences for the health state of the forests. These climatic variations influence the duration of the growing season, inducing plastic adaptative responses in trees as the formation of intra-annual density fluctuation (IADFs) in the tree-rings. IADFs have an important role in trees' water use, productivity, physiology, and resilience of the species. In this study we combine xylogenesis analyses with sap flow monitoring over a complete growing season of *Pinus pinaster* Aiton forests, located in a very hot and dry area of the Vesuvius National Park in southern Italy, to understand the climate-adaptative responses of this widely diffused and utilized species in the Mediterranean region. For the first time it was possible to follow the phenological formation of IADFs in tree rings and link them to water use dynamics with high temporal resolution.

Our preliminary results showed a particularly long growing season of the monitored trees: the cambial activity persisted from early spring to the first months of winter, suggesting that the temperatures of this area were not low enough to induce a complete xylogenesis dormancy. The Pine stand followed a bimodal growth pattern: the trees reached a first peak of productivity in spring by forming wide early-wood cells, afterward they reduced the cambial activity during the hot and dry summer period, forming thick late-wood cells. Finally, in autumn when climatic conditions returned favourable, we found a second growth peak characterized by formation of IADFs with new earlywood-like cells in the last part of the ring. The continuous monitoring of sap flow recorded over the year reflected the observed growth pattern: trees lowered their water use during the summer drought to counteract water loss and xylem cavitation, while they increased the transpiration in the two most favourable seasons of spring and autumn favouring the carbon assimilation and growth.

Overall, our findings suggest that maritime pine is a species highly adapted to the Mediterranean climatic conditions, capable of reacting plastically to the extreme stresses induced by global warming. However, if climate change rates increase as predicted, this species may no longer be able to survive in the future. Therefore, our monitoring activity will continue for the next growing seasons with the aim of identifying its tolerance threshold to climatic stresses.

Drought adaptation of Italian silver fir genotypes in a climate change perspective

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Resilience of Mediterranean forest ecosystems is closely linked to their ability to adapt to drought and increasingly hot temperatures. Such ability can be influenced by genetic differences between and within species, or provenances. Therefore, it is essential to define management guidelines that consider the role of local provenances in forest adaptation to climate change, and to promote the conservation and sustainable management of resilient forest genetic resources.

In this study, we analyse growth responses to drought of silver fir (*Abies alba*) in the Tuscan-Emilian Apennines National Park, while comparing the physiological performance of three provenances of this species in Italy: (a) Piedmont - (b) Northern Apennines (local) - (c) Southern Apennines. Drought severity was defined through the Standardised Precipitation-Evapotranspiration Index (SPEI). We carried out dendrochronological analyses by assessing climate-growth relationships, applying drought 'resilience indices' (RRR) based on tree ring width, and estimating water use efficiency (iWUE) through carbon isotope analyses ($\delta^{13}\text{C}$) on wood samples. Finally, we used FORMIND, an individual-tree process-based model, to simulate growth under two climate scenarios (R.C.P. 4.5 and 8.5). We used field data to parametrize allometric and growth equations used by FORMIND to describe provenance-specific behaviour. Artificial forests had a faster growth than natural forests ($\text{BAI}_{\text{art}}= 16.4 \text{ cm}^2$, $\text{BAI}_{\text{nat}}= 13.2 \text{ cm}^2$), also showing higher resilience during severe droughts and higher recovery during severe and extreme droughts. Fir provenances differed slightly in growth rate ($\text{BAI}_a= 17.5 \text{ cm}^2$, $\text{BAI}_b= 19.0 \text{ cm}^2$, $\text{BAI}_c=22.8 \text{ cm}^2$), with higher performance by the southern provenance. The southern Italian provenance also had better recovery and resilience during moderate and extreme dry years. Preliminary modelling results confirmed these trends, even if the differences between climate scenarios were not significant. Isotope analysis on tree rings will be performed soon.

The workflow proposed in this paper couples morphological with eco-physiological analyses, allowing a comprehensive overview of tree response to drought. These results provide important information on the adaptive response of silver fir under climate change, underlying the importance of local genetic diversity for adaptation. Southern provenances have shown better growth and resilience against drought, proving to be a very important resource in a

climate change perspective. Thanks to the strong collaboration with the National Park and local forest managers, these results may find concrete application e.g. by planning assisted migration activities in the Park forests, and providing better protection of local fir provenances in natural forests.

Extreme climate signals recorded in Icelandic shrub growth-ring chronologies: A multi-species approach in sub-Arctic climate

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This study presents the first comparison of the radial growth chronologies of six dwarf shrub species from Iceland. The study site is located in the northeastern part of the island, in a hilly volcanic upland, on the northeastern edge of the Þistilfjörður fjord. The average annual temperature in Raufarhöfn is 2.6 °C, while the temperature of the warmest month (July and August) is 8.5 °C, influenced by the warmth of the Gulf Stream. The region averages 662 mm of annual precipitation. The driest months are May (29 mm) and June (33 mm). Since the 1980s, temperatures have been increasing by about 0.18 °C/decade. Most of the land surface in the study area is sparsely vegetated or unvegetated. Arctic–alpine tundra, composed mainly of various species of dwarf shrubs, is the predominant vegetation type in Iceland. Thus, for a detailed dendrochronological investigation, shrub and dwarf-shrub species were selected: mountain avens (*Dryas octopetala*), dwarf juniper (*Juniperus communis nana*), dwarf willow (*Salix herbacea*), Arctic willow (*Salix arctica*), dwarf birch (*Betula nana*) and black cowberry (*Empetrum nigrum*). Although they are common, their potential has not been sufficiently analysed so far.

A total of 60 living shrub samples were collected in the field and processed according to the well-known protocol for dwarf-shrub chronologies, including serial sectioning procedures and measurements along several radii. For each species, a local chronology was created, spanning from 50–56 years (dwarf juniper, dwarf willow) to 60–80 (crowberry, mountain avens). Dendroclimatological analysis confirms that June and summer months' above-average temperature positively influences the growth of most species. The opposite reaction is observed for willow species; the climate–growth correlations indicate that these species positively respond to winter and summer precipitation, as well as negative correlation with the June temperature. *Salix* species are valuable drought indicators in NE Iceland. Other species, for example, *Dryas* and *Juniperus*, provide valuable information on how low Arctic tundra communities react to temperature changes. The first network of Icelandic shrub chronologies allowed for assessing the impact of extreme conditions on the growth of selected shrubs species. Extreme climatic conditions leading to the creation of very low growth or changes in wood anatomy (frost ring and blue ring) were determined. Weather conditions in 1979, the

coldest year of the entire meteorological series, have been subjected to a detailed analysis. Multispecies shrub network from northern Iceland is important for the proper understanding of different meteorological threats of the Low-Arctic tundra.

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Age-related responses of larch trees to climate warming and the underlying physiological mechanisms in the boreal permafrost region of Northeast China

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The rising atmospheric CO₂ concentrations (Ca) has been believed to enhance intrinsic water-use efficiency (iWUE) and subsequently to increase tree growth in boreal regions. However, age-related iWUE changes, their interaction with climate change and their effect on tree growth are still poorly understood. Here, we measured tree-ring $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, compared the relationships between iWUE and tree-ring growth over 70 years for young (85±6 yr) and mature (225±35 yr) *Larix dahurica* trees in boreal permafrost region of northeast China.

Climate data show that the temperature during 1985-2018 (warming period = WP) was significantly higher than that during 1951-1984 (basic period = BP) in the study area. The tree-ring growth rate for both mature and young larch trees did not change during BP, but the mature larch trees, and not the young ones, significantly increased their growth rates during WP. The tree-ring $\delta^{13}\text{C}$ was not correlated with $\delta^{18}\text{O}$ for both mature and young larch trees during BP, but they were significantly positively correlated only for mature trees during WP, suggesting a strong stomatal response. The iWUE of mature trees increased during the entire period from 1951 to 2018, whereas it increased in the young trees only during WP. Commonality analyses indicated that Ca rather than climate had the strongest effect (>36%) on iWUE for both young and mature larch trees. The iWUE showed a weak relationship with tree-ring growth for young larch trees during both BP and WP. By contrast, iWUE (23.6%) showed strongest effects on tree-ring growth for mature larch trees during WP. Our results indicate that mature larch trees displayed higher sensitivity to air warming and Ca increase than young ones. We also show that stomata played an important role in enhancing iWUE and tree growth under warming. The present study suggests that using dual isotopes in tree-rings helps in elucidating the different physiological mechanisms in young and old trees as response to climate change.

Recent climate warming differently affects dominant broadleaf and conifer species in northern Patagonian forests

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The Patagonian forests are facing the impact of global climate warming displaying diverse responses across species distribution ranges. Hotter and dryer climate was registered during the last decades in northern Patagonia, with future predictions forecasting an increase in this tendency. Despite recent studies, the vulnerability of forests to climate change is still understudied considering site-specific habitat factors. The disturbance regime of Patagonian forests, such as fire events enhanced by climate extremes, adds complexity to predicting forest responses. Thus, we investigated the effect of recent climatic changes on tree radial growth trends as an indicator of tree vitality and vulnerability, in three native, dominant tree species of the Andean Patagonian forests (broadleaf deciduous *Nothofagus pumilio*, evergreen *Nothofagus dombeyi* and conifer *Austrocedrus chilensis*).

We selected 24 monospecific stands across the west-east precipitation gradient in the Argentinian sector of the Rio Puelo basin. The basin is located in the north Patagonian Andes where the mountain range blocks the humid westerlies creating one of the steepest pluviometric gradients in the world. The landscape is shaped by glacial erosion and fertile volcanic soils.

We calculated ring-width series for each forest stand, from the humid sites in the west to the more arid ones in the east. For each chronology, we computed the annual basal area increment (BAI) from bark to pith using individual tree diameters at breast height (DBH). Using the detrended ring-width index series (RWI), the series sensitivity, namely the mean inter-annual variability, was quantified by the series coefficient of variation. Within-population growth synchrony, as an indicator of common susceptibility to climate variation, was estimated by the mean correlation among RWI series (R_{bar}).

The native conifer *A. chilensis* stands presented the highest growth synchrony in all sites, with a strong increase from the previous (1942–1981) to the current (1982–2021) observation period. The evergreen *N. dombeyi* followed a similar trend, mostly in the young stands. In contrast, lower synchrony values were observed at wetter sites for the deciduous *N. pumilio*

stands. Sensitivity increased from previous to current period in all sites for the three species with the exception at the humid *N. pumilio* stands, where the sensitivity decreased recently, indicating that climate warming affects these particular sites less. Basal area increment (BAI) significantly decreased in the last 40 years in all *A. chilensis* stands except in the driest site, where the oldest stand occurs, hinting towards a possible drought acclimation or adaptation. Similar trends were observed for old *N. dombeyi* BAI at drier sites, where micro relief characteristics could be playing a major role modulating radial growth.

Our findings present insights into the recent, diverse effects of rapid climate warming on the native, dominant tree species of the north Patagonian forests across precipitation gradients. Growing at harsher, wind and radiation-exposed sites, *A. chilensis* stands appear as the most vulnerable species to a warmer and drier climate. The vitality of the evergreen *N. dombeyi* forests seems to depend more on specific habitat conditions. Growing towards the upper treeline, *N. pumilio* stands at humid sites could be currently profiting from climate warming, with contrary effects towards more exposed and xeric sites in the east.

Analysis of divergent trends in radial growth and functional traits in cork oak (*Quercus suber*)

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Increases in the frequency and intensity of drought conditions will influence plant growth and productivity, particularly in areas already subject to water availability limitations such as the Mediterranean. Indeed, a decline in cork oak (*Quercus suber*) productivity has already been noted in Portugal in the last decades. As cork oak is of high ecological, and socio-economic value for this region, it is thus imperative to better understand the underlying mechanisms and intra-specific differences in growth vulnerability to drought for conservation of this species.

Dendrochronological techniques are particularly useful to understand tree growth vulnerability to drought as they allow us to observe growth patterns over time. In addition, the integration of wood anatomical analysis of traits related to hydraulic functioning such as Mean Vessel Area (MVA) and Vessel Density (VD) may also shed light on the response of tree growth and functioning to drought.

Therefore, to identify potential intra-specific differences of cork oak growth in response to drought conditions, we selected trees from sites across a gradient of long-term rates of decreasing water availability within the main distribution of cork oak in Portugal. In addition, within each site we selected trees from contrasting long-term spectral trends of vegetation greenness (Normalized Difference Vegetation Index – NDVI) and differing levels of canopy defoliation, two proxies of tree health. This allowed us to observe radial growth in response to differing trends of water availability as well as the potential intra-specific differences between individuals of differing health status. We focused on dendrochronological and wood anatomical analysis of cork oak branches as the inter-annual boundary of growth rings from the main stem are notoriously difficult to identify.

We hypothesize that (i) there will be intra-specific differences in radial growth and anatomical features between areas with differing trends in water availability, however, (ii) significant differences between tree individuals of differing health status will be more prominent. This work will serve to elucidate the vulnerability of tree growth to drought, which is vital in better understanding the scope of impact climate change may have on cork oak in this region.

Global change effects on Mediterranean pine forests: hotspots of dieback

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The effects of climate extremes on the vulnerability to forest dieback of widely distributed Mediterranean pine species are poorly understood but important for forecasting their responses to climate change. As air temperature increases, evaporative demand will also rise, exceeding the drought tolerance of tree species to pervasive droughts. Using a spatially comprehensive network of six pine species with > 800 tree-ring chronologies, > 500 plots from the the ICP-forest network (defoliation, mortality, etc) and drought-induced mortality database combined with NDVI (Normalized Difference Vegetation Index) encompassing the wide ecological and climatic gradients across Mediterranean Basin. We show that an increase of climate water deficit produced legacy post-drought effects on growth with strong variation in growth across its distributional range, but common patterns were found within each provenance. Vulnerability to legacy effects of extreme droughts were most prevalent in dry provenances and western, in contrast to limited legacy effects after drought observed in wet provenances and high-elevation sites. Post-drought legacies decreased with latitude and wetter conditions but decreased with spring precipitation in western mediterranean. Trees from dry, rear-edges sites in the Mediterranean Basin were more vulnerable to recurrent droughts than trees from wet. The increase in summer temperature and evapotranspiration favour hotter droughts that can increase defoliation, decrease tree growth and productivity causing drought-induced forest dieback in drier regions over the next decades.

Extracting heritable variation from tree-rings allows for precision breeding in a changing climate

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Conifers are ecologically dominant and economically important, but under climate change mature trees are no longer adapted to their environment and are succumbing to drought, disease, early-budding and other challenges globally. If we could predict how individual tree genotypes would respond to different environments, we could — given environmental predictions — plant the right tree in the right space.

Tree growth is a function of the experienced (macro- and micro-) environment but also the genetics that underlie how an individual tree responds. While tree-ring studies are dominated by a focus on environmental responses, increment cores also carry signal from tree-specific, genetic responses. Using models derived from agricultural genomics, we isolate variation associated with tree-level genetic signals as well as tree-specific responses to environments modelled from historical weather station data.

Confirmed using genetic relationships from millions of genetic variants (single nucleotide polymorphisms, or SNPs), these estimates are highly heritable and can be passed on to offspring. This makes them useful as responses in prediction modelling to evaluate tree performance in new environments and in association mapping to understand the genetic basis of how trees adapt to new environments. As environments shift under climate change, this approach promises a powerful tool to select parents for healthy, resilient forests.

Response of coniferous species to past extreme climate events

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Recent episodes of unusually warm summers and autumns and periodic dry spells rise concerns about the growth of forests in Southern Europe including Bulgaria. Among those species, which could be expected to be at highest risk are mountain conifers, which are adapted to cooler mountain climate. Besides drought stress they could experience more competition from advancing deciduous species from lower altitudes and at the same time have limited possibilities for migration to higher altitudes. This rises the need to better understand the response of certain species to past extreme climate events as possible clue for their capabilities to cope with similar conditions in future.

We studied the changes of tree-ring width in the major coniferous species in the mountains in southwestern Bulgaria - *Pinus peuce* Griseb., *Pinus heldreichii* H. Christ, *Picea abies* (L.) H. Karst., *Abies alba* Mill. and *Pinus sylvestris* L.. We studied tree-ring cores collected from trees growing at typical for the species locations. Only for *Pinus peuce* in addition we studied extremely low location for the species distribution. We calculated the changes in tree-ring width in selected extreme years (cold and wet summers or hot and dry summers) and the years following them to get insight into the immediate response of trees and the years needed for recovery. We calculated the change compared to the average growth of the 10 years prior to the extreme year.

We found that the species respond more sharply to hot and dry summers with growth reductions lasting up to several years. This was most expressed in the extremely low location of *Pinus peuce*. Pines responded to dry summers with short-term growth reductions and recovered quickly. As expected *Picea abies* and *Abies alba* also responded negatively to summer drought. The studied species did not respond synchronously to colder and wetter summers. Usually they had reduction only in the specific extreme year but that did not cause negative legacy. From our previous data we know that in such years the response is mostly in the anatomical structure by producing light rings and also associated reduction in maximum latewood density.

Our data indicates that the main concern for the growth of the studied coniferous species could be increasing summer temperatures especially if coupled with drought episodes. More frequent years as these could have negative impacts on the growth and loss of vigor which could lead to further health problems.

Assessing the growth response of silver birch to climate change through a combined tree-centered approach based on dendroecology, dendroanatomy and daily stem size variations monitoring

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In Europe, some main timber species, notably Norway spruce and common beech, are threatened by the extreme climatic events, especially droughts caused by climate change. This phenomenon raises concern among forest managers explaining the critical need to identify tree species that would ensure the resilience of European forests and favour a sustainable adaptive management. In this context, silver birch (*Betula pendula* Roth.) could play a key role in the future forest diversification: its large ecological amplitude goes with a remarkable capacity to colonise diversified environments, even the most constraining. Despite such characteristics, the climatic sensitivity of silver birch has been barely investigated in Europe. To address this issue, I will use three combined approaches, detailed below.

Firstly, the long-term growth response of silver birch to past climatic events will be assessed throughout the bioclimatic gradient of the regional scale of Wallonia (Belgium). Then, the future growth trends will be assessed in Europe using tree-ring width data from the GenTree database under different climatic scenarios. Secondly, I will link tree structure to tree function by studying the impact of extreme climatic events on xylem anatomical traits and more specifically, the wood intra-density fluctuations using X-ray CT scan method and quantitative wood anatomy. Finally, the influence of soil water availability on growth daily variations will be studied at the scale of a forest massif along contrasted forest sites using automatic radius dendrometers.

Climate modulation of carbon sequestration in Scots Pine stem wood: A Scottish multi-transect approach

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Elevational transects offer a perfect opportunity to examine the effect of climate on tree growth within a constrained area. This study examined how specific local climate at 34 sites along elevational transects (~3°C temperature range) within three river catchments (the Spey, Dee and Tweed) in central and eastern Scotland modulate the carbon sequestration (CS) capacity of Scots pine (*Pinus sylvestris*). We sought to establish if simple additions to the normal 'dendroclimate' sampling protocol could yield credible estimates of the annual variability of CS in Scots Pine stem wood, without the need for long term monitoring apparatus which is typically lacking at natural old growth forest stands. Further, focusing on semi-natural and old plantations, CS estimates could be calculated further back in time than would be possible using experimental plots. The caveat being, however, that factors such as ecological and anthropogenic disturbances, cannot be controlled for, therefore imposing a greater amount of non-climatic 'noise' on the data. Using a combination of existing and new ring-width chronologies, basic tree dimension data and bulk density measurements, timeseries of annual CS in stem wood were produced for each site. These suggest, unsurprisingly, that sequestration is highly site specific and that localized disturbance events have significant impacts on CS. Making direct comparisons of sequestration rates between sites was initially complicated as the sites varied in mean age (~150-300 years, with some trees > 500 years) and have therefore experienced varying climates through time. By extending the instrumental record, using a multi-centennial (tree ring based) temperature reconstruction (N-CAIRN), we were able to create an age and temperature dependent model of stem wood CS in Scots pine, facilitating the direct comparison of juvenile, through to mature trees across all sites. This model predicts that a 25-year-old Scots Pine growing at a site with a summer temperature of 14°C (approx. <100masl) will sequester significantly more carbon annually than a 75-year-old Scots pine growing at a 10°C near tree-line site (approx. >550masl). These results have important implications for strategic tree planting as a nature-based solution to meet Scottish net zero targets set for 2045. Finally, although our results are specific to Scots pine in Scotland, such dense elevation transect studies and the simple methodologies to utilize existing tree-ring chronologies employed here could easily be applied to other regions and species.

Genetic and environmental contributions to growth habit in Mugo pines

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Pinus mugo complex, a variety of species referred to Mugo pines, grow at high altitude in the European mountains, including the Pyrenees, the Alps, and the Carpathians. Species of this complex represent different forms of growth: from serpentine to upright trees.

Mugo pines are exposed to different environmental and successional effects during which changes in plant functional traits may appear. Mountain pines are also spatially isolated which can impact their genetics. It is still not clear what tree growth form being more advantageous and why, both genetics and environment might have an impact. What is the basis of differences in growth form habit in mountain pines? To find it out we are measuring both successional and individual effect by tree cores, genetic effect by DNA samples and successional effect by the set of environmental parameters.

For this study we have chosen a unique population of Mugo pine species in the upper part of the Wimbachtal in the centre of Berchtesgaden National Park (Germany), which is unusual in the sense that it includes all growth forms: serpentine trees, upright trees, and intermediate shapes. The valley is isolated and there are seasonally active debris flows, that work as disturbance factor and drive succession. We sampled genotypes and phenotypes of diverse growth forms across 24 highly heterogeneous plots, which were also characterized for ecological traits, from transects oriented across successional environments perpendicularly to the main debris flows. We measured more than 15 environmental parameters, including altitude, plot coverage by perennials, humus depth, etc. Cambium for reduced representation sequencing and associated phenotypes were collected for 16 trees per plot.

Phenotypes include height of the tree, tree cores (age), the growth form, which we define as the inclination angle of trunk (we split the tree into thirds and for each third evaluated angle as 0, 30, 60, 90 degrees). Regression modelling will elucidate the relative importance of genetics, generation, and environment on growth habit. Population dynamics between the growth forms across the valley will be assessed with population genetic analysis. Genome-wide association studies can hopefully identify genetic variation associated with differential growth.

The results should give us an outlook on ecological and population dynamics of mountain pine and growth form.

Disentangling the different climatic responses of radial growth and $\delta^{18}\text{O}$ variations of evergreen and deciduous conifers in terms of the Southern Tibetan plateau

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The Tibetan Plateau (TP), often called "The Third Pole, " is more strongly affected by climate change than other regions on earth. The long-term climate trends, as well as the recent change in extreme climate events on the TP imposed both acute and long-term impacts on plant growth and physiology of tree species growing in climate-sensitive high-elevation sites. In this research, we selected two native conifer species, namely the deciduous *Larix potannini* and the evergreen *Abies georgei* on the southern margin of the TP to compare inter-annual growth variability and tree-ring cellulose stable oxygen isotope variations and their relationships with the climate. The inter-annual growth pattern of the two studied species derived from tree-ring width (TRW) chronologies showed a strongly diverging trend after 2000 CE., evidenced by their response to different climate variables. *Larix potannini* radial growth was strongly favoured by warmer temperatures, especially during summer (June-September), with insignificant response to precipitation. In contrast, *Abies georgei* TRW showed a significant correlation with rainfall, but an insignificant relationship with temperature. In order to further disentangle the climate response of the two species belonging to different functional groups, we analyzed tree-ring cellulose stable oxygen isotope ($\delta^{18}\text{O}$) variations. *L. potannini* showed a substantially lower mean $\delta^{18}\text{O}$ value compared to *A. georgei* (3.07‰, $p < 0.01$). However, both $\delta^{18}\text{O}$ chronologies correlated strongly ($r = 0.72$; $p < 0.01$) with each other. In line with previous studies on the TP, both $\delta^{18}\text{O}$ chronologies showed strong negative correlations with precipitation and atmospheric moisture content (relative humidity) of the entire growing season (May-October). $\delta^{18}\text{O}$ of the evergreen species (*A. georgei*) showed a statistically significant positive relation with May-September temperature, whereas the deciduous species (*L. potannini*) was neutral to temperature. The higher $\delta^{18}\text{O}$ value of *A. georgei* indicates the utilization of source water from a shallower water pool compared to *L. potannini* which was also reflected by the significant response of *A. georgei* TRW chronology to moisture and its $\delta^{18}\text{O}$ series to temperature. The available moisture in the upper soil layer is more prone to drier atmospheric conditions controlling the growth of the tree. Similarly, the source water in

the upper soil layer has more enriched $\delta^{18}\text{O}$ due to evaporation which is greatly influenced by atmospheric temperature. Our results showed that, within the same site, evergreen and deciduous conifer species could imprint different climate signals in radial growth and $\delta^{18}\text{O}$ series that might be combined to reconstruct different climate variables. The in-depth examination of such differential climate responses in TRW and $\delta^{18}\text{O}$ can be a crucial step in understanding their adaptation strategy during extreme events like drought and formulating mitigation plans in forest management.

Climate-growth relationship of spiny monkey-orange (*Strychnos spinosa* Lam.) from Benin

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This study aimed to investigate the effect of climate variability on growth dynamics of *Strychnos spinosa*, a multipurpose tree. Stems disks (41) were collected in Benin to establish species-specific local chronologies of tree growth, from less disturbed environments (National Park and classified forest) in the Sudano-Guinean (SGZ, 03 sites) and Sudanian (SZ, 03 sites) climatic zones. After air-drying the stem disks, they were polished gradually using sand paper of grit size 400-2000. Dust was removed from the wood surfaces to improve visibility of the growth zone boundaries. On the sampled disks, each ring was marked on 2-3 radii and every tenth ring was interconnected between the different radii. All ring widths were measured perpendicular to ring boundaries along the radii along using LINTAB 6 (Rinntech, Heidelberg Germany). Mean curves were produced for each disk and study site using the radii. After visual cross-dating (with reference to pointer years), ring-width series were statistically cross-dated using TSAP software. Two statistical indicators (GLK; t-value) were used to evaluate the match between the time series and select the best correlated series included in building sites chronologies. The relationship between climatic parameters and radial growth of the trees was assessed after detrending and standardization of the individual growth ring width series. Pearson correlation analysis was conducted for the RWI and the climatic parameters (Rainfall and Temperature). The results revealed that the samples were young (11-31 years). Cross-dating of individual tree-ring patterns was successful for 12 and 11 samples respectively from the SGZ and SZ. The mean annual growth rates of *S. spinosa* in the two climatic zones varied suggesting that climate influences the growth of the species. Moreover, the rainfall happens to be strong climatic forcing parameter that controlled *S. spinosa* growth.

Assessment of the climate-growth responses of Norway spruce in the Tatra Mountains, Slovakia

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The earth's climate is changing with a projected increase in frequency and intensity of extreme climatic events. These climatic events are more often prominent at species-specific distribution limits which result in a substantial change in the structure and function of species. To be able to understand how exactly forest ecosystems will be influenced by changing climate, it is necessary to gain a clear picture of tree and forest growth dynamics in times of climate change. In our study, we analyzed the growth responses of Norway spruce *Picea abies* (L.) H. Karst to climate based on over 350 individual trees from two sites near Javorova and Popradskepleso, Slovakia with different bedrock condition i.e. limestone and granite. Each site contains a forest and treeline plot of around one hectare. Individual spline detrending was used to retain annual to multi-decadal scale climate information in the data. The growth response for the period 1960 to 2021 was divided into two periods of 30 years each. Between these periods, we found a slight shift in the trees climate sensitivity. Previously, ring-width chronologies correlated significantly ($P < 0.05$) and positively with late spring and early summer months (May-June) temperature in the forest and treeline from both sites. However, during the last 30 years, the trees located at the Javorova forest sites only respond to July temperature in comparison to the trees located at Popradskepleso sites, which significantly correlate with July- August temperature in both plots. Similarly, our result showed a positive response of the maximum latewood density chronologies to the temperature of May, August and September during the period (1960-1990) at both sites, while there is no significant response from 1991 onwards. Preliminary findings suggest that Norway spruce from two nearby sites with different geological setting show different response to climate change but the potential underlying mechanisms will be further investigated.

Microsite effect on the climate sensitivity of Norway spruce in a karst landscape of the Franconian Jura

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Drought is an increasing problem for the growth and development of forests throughout Europe, especially for drought sensitive species such as Norway spruce (*Picea abies* L Karst). In karst landscapes, the geological and hydrological conditions enhance the negative effects of summer drought on trees even in regions with sufficient annual precipitation. Soil conditions in these landscapes are also known to be highly heterogeneous in terms of micro-topography, which can lead to differences in water availability even for trees that grow close to each other. This is the case of the area in the Franconian Jura where we had the opportunity to study the growth response of Norway spruce to climate during the 32nd European Dendroecological Fieldweek in Heiligenstadt, Germany.

We aimed at capturing the differences in climate sensitivity of three Norway spruce sites situated in the same area – a small karst valley but with different microsite characteristics. The first site (bottom) is located at the valley along a little creek, the second site on a slope, and

the third one on a plateau. The three microsites are located close to each other from 470 to 540 m asl. 135 trees were cored using an increment borer (34 – 54 per site). The forest is a planted stand with natural regeneration. Therefore, the age of sampling trees varies from 24 to 143 years, with most trees being younger than 60 years. Tree-ring width (TRW), earlywood (EWBI) and latewood (LWBI) blue intensity were measured on scanned images.

At all three microsites, the radial growth of Norway spruce is mainly driven by water availability during summer and early autumn. The growth-climate signals found in TRW are similar for the three sites, with the strongest correlation in the plateau site, as opposed to the valley one. In comparison, growth-climate responses of both EWBI and LWBI show a higher variability between the microsites.

The use of different tree-ring proxies emphasised differences in climate responses between microsites and provided complementary insights. The combination of blue intensity proxies was the best to capture the differences between the microsites. Additional analyses, including the assessment of intra-annual density fluctuations will further improve our understanding of how tree growth and climate sensitivity vary across these three microsites. The results are relevant to adapt regional forest management to the expected increase in drought occurrence.

A new species in dendrochronological research - *Prunus avium* L.

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The wild cherry (*Prunus avium* L.) is one of the most valuable native trees in our forests. It has accompanied humans since at least the Neolithic, and has been in cultivation since at least the 8th century BC (in the gardens of the Assyrian king Argon II in Mesopotamia). In forests, the wild cherry has a high biocenotic value; it enriches biodiversity, strengthens the resistance of forests, and enhances the aesthetic and landscape values (especially during flowering in spring). The fruits of the wild cherry represent the food base for many animals. It reaches a height of up to 20-30 m, and a DBH of up to 40-60 cm. It is considered as fast-growing but short-lived (the age of the oldest specimens is estimated at 100-150 years). The wood of *P. avium* is most often referred to as diffuse porous, sometimes as semi-ring porous, with annual increments (tree-rings) visible. There is a narrow sapwood layer and the heartwood is reddish brown. The wood is valued as hardwood for woodturning, manufacturing cabinets, musical instruments, inlays and veneers. The natural range of the wild cherry occurrence includes mainly Central and SE Europe, the SW part of Asia and a small area in the NW part of Africa. The northern limit of the species range extends through Poland. However, in Poland, the wild cherry is found far to the north of this designated border, which results from the artificial introduction of this species as an admixture into forests. In Poland, this species grows in the lowlands, uplands and mountains, reaching the upper limit at an altitude of 1150 m above sea level.

There are no reports on tree-rings (tree-ring width, growth rate in different phases of the tree life, no identification of anomalies in the wood structure, no studies on tree-ring/climate relationship, tree-ring/habitat relationship). The available literature contains scattered opinions or statements that the wild cherry is a fast-growing tree; that it lives between 70 and 100 years or 80 to 100 years or up to a maximum of 100 to 120 years or 100 to 150 years; that tree-rings are visible and evenly distributed; and that wild cherry wood from northern Poland and Germany is highly valued due to its narrower tree-rings.

The pilot study results obtained from sites located outside the natural occurrence area of the wild cherry in Poland (Strzelce Krajeńskie, ST, and Szczecinek, SZ, Forest Inspectorates), suggest that summer rainfall sum is the main factor shaping the growth reactions. High rainfall sums and sufficient water supply to the habitat resulted in a positive growth reaction and an increase in tree-ring width. Conversely, rainfall shortage and drought caused a decreasing

growth trend and growth depressions. However, the differences among the results obtained from various dendroclimatological analyses (various relationship periods, varying relationship strength, differing meteorological conditions indicated for different sites) indicate that further research is required.

Sensitivity of $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $\delta^2\text{H}$ to vapor pressure deficit in silver fir and Douglas fir individuals experiencing different competition and species diversity

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With extreme climatic events occurring more frequently due to climate change, understanding climate sensitivity of trees and their drivers is becoming increasingly important. Silver fir (*Abies alba* Mill.) and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) are two interesting softwood timber species for forestry in Central Europe and are thought to be relatively more drought tolerant than Norway spruce (*Picea abies* (L.) H. Karst.). However, it is not yet clear how competition and species diversity influence the radial growth response of silver fir and Douglas fir and even less their physiological response to climate. We measured triple isotopes ratios ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $\delta^2\text{H}$) in tree-ring cellulose of 48 individuals of silver fir and Douglas fir for the period 2000-2020. All three isotope ratios were sensitive to the spring and summer vapor pressure deficit (VPD) for both species. Competition had a significant and negative effect on $\delta^{13}\text{C}$ for silver fir. Species diversity influenced the response of $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $\delta^2\text{H}$ to vapor pressure deficit (VPD) for silver fir but not for Douglas fir. Besides, this new dataset including $\delta^2\text{H}$ ratio will help better understanding the physiological processes driving the water use strategies in silver fir and Douglas fir. Relationship between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ was significant and positive for Douglas fir at the individual level. For both species, $\delta^2\text{H}$ had a strong and negative correlation to tree-ring width. Finally, VPD was also changing the strength of the correlation between the variables in many cases (i.e., significant interactions in the mixed-effects models). We conclude that combining different isotope ratios as well as radial growth information under the influence of competition and species diversity provides new information on the water use and climate response of silver fir and Douglas fir.

Seasonal temperature signal in treeline Maximum Latewood Density records of Great Basin Bristlecone pine samples from the California White Mountains

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Great Basin Bristlecone pine (*Pinus longaeva*) (PILO) trees are known for their old age. The longest tree-ring width (TRW) chronology is more than 9000 years long, and the temperature-sensitive upper treeline TRW chronology extends back to 4410 BC. The TRW patterns of upper treeline bristlecone pine trees are influenced by temperature variability at decadal to centennial scales, but careful site selection needs to be considered in order to have a stationary and consistent response. Maximum Latewood Density (MXD) is a tree-ring proxy that is strongly linked to past inter-annual temperature in the northern hemisphere. PILO wood offers the possibility to extend current MXD chronologies, but PILO MXD records are currently non-existent due to technical burdens such as the twisted grain angle of the wood. Here, we present a 688-year X-ray Computed Tomography (X-ray CT) MXD chronology of PILO to investigate the inter-annual temperature signal at upper treeline sites. 69 crossdated cores were analyzed from four upper-elevation sites at various elevations, with the oldest sample dating back to 1069 CE. We developed a MXD chronology that correlates significantly positively with maximum summer (April-September) temperature. The significance level as well as the spatial extent of the correlation increases with altitude. Our results suggest that bristlecone pine MXD chronologies can be used as a proxy for western North American summer temperature variability over the past centuries to millennia.

The impact of temporarily suppressed trees in stand-wide climate signals

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Increasing droughts are deeply affecting large-scale forest growth dynamics. The impact at individual tree level is, however, determined by numerous intrinsic factors and physiological mechanisms, resulting in highly individualistic tree responses possibly diverging from the general population. Twenty Scots pine stands in SW Germany were used to assess the individual tree responses to the 1976 drought, one of the direst years in Central Europe in the last century. Trees showing a prolonged post-1976 growth reduction were considered suppressed and compared with neighboring, “control” trees. Independent of drought intensity and mean climate conditions, we observed varying proportions of suppression within the forest stands, and in most cases, the growth reductions lasted more than a decade indicating extended drought legacy effects. The divergent growth trajectories between suppressed and control trees yielded contrasting results in the resilience analysis. Temporarily affected trees showed a 50% reduced capacity to return to their original state as well as a drop in resistance over four years indicated by lower recovery rates and longer recovery periods. Moreover, control and suppressed tree chronologies revealed temporally varying climate correlations as distinct transformations before and after the 1976 drought became evident. Particularly suppressed trees indicated an increase in sensitivity to maximum temperatures and summer droughts.

Development of Dendrochronology and its pace in China since 1990

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While dendrochronology is nowadays a frequently applied method for climate and ecological studies worldwide, its very dynamic development in China has hardly been elucidated. Here we performed a bibliometric evaluation on the rapid development of dendrochronology and revealed China's place in the world over the past 30 years. We built search formulas in the Web of Science Core Collection and presented a comprehensive overview according to the annual document outputs, research categories, journals, high-frequency keywords, etc. The results showed that (1) The increase of publications on dendrochronology exhibited a continued increase during the past 30 years. China's contribution to global documents has reached nearly 12.34%, the second highest in the world compared to the highest number of USA (21.60%). Among institutions, the University of Arizona and WSL had the largest number of publications, with the most published accounting for 4.48% in total, which was close to the Chinese Academy of Sciences. (2) The cooperation of within global research efforts adhered to the spirit of win-win cooperations. The importance of China (0.09) in the cooperation network has reached half that of Switzerland (0.15) and the United States (0.15) in accordance with PageRank over the past 10 years. (3) Global research directions focused on the innovation for new methods, with interdisciplinary studies among the most published papers, whereas China focused more on climatology. Global average Local Citation Scores (LCS) and Global Citation Scores (GCS) were about four times and seven times that of China. (4) The research of traditional dendrochronology was quite mature. The integration in interdisciplinary studies such as ecosystem productivity, using additional techniques including remote sensing, artificial intelligence and modeling was the hotspots for realizing diversity, innovation and universality. (5) Collaboration and publication worldwide through online journals have not been greatly affected under COVID 19. A comprehensive understanding for the research dynamics of dendrochronology can provide inspiration for the future development of dendrochronology for China.

Plasticity of xylem functional traits contributes to tree performance and survival of Mediterranean conifers under drought stress

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Forests are threatened globally by more frequent and intense droughts. Understanding the complex processes determining tree vulnerability to drought is crucial to predict potential changes in species composition under future climatic changes. Functionally close and coexisting species may exhibit differences in drought-vulnerability that could cause niche differentiation and ultimately affect forest dynamics. In this study we used different spatio-temporal and ontogenic scales to characterise the decline of *P. pinaster* in comparison to a more drought-tolerant, co-occurring species *P. pinea*. We extracted core samples from trees with different health status (i.e. healthy, declining and/or dead) from both species and evaluated the response of each different group to drought-stress using dendrochronological growth, quantitative wood anatomy and $\delta^{13}\text{C}$ series. Additionally, we studied the effect of water stress in the xylem architecture and $\delta^{13}\text{C}$ leaf content in seedlings from both pine species. The mortality pattern in adult trees differed between species. Growth decline previous to mortality in *P. pinaster* was more extended in time in non-healthy trees with lower growth than in healthy trees, suggesting the presence of a long-term stressor. The xylem response to interannual climatic variability was more plastic in healthy than in non-healthy trees. In response to drought, healthy pines developed higher xylem safety by either reducing lumen area (*P. pinaster*) or by reinforcing cell-walls (*P. pinea*). Declining and dead pine trees exhibited similar discrimination against ^{13}C than healthy trees. Therefore, remaining leaves in highly defoliated canopies in non-healthy pine trees maintained lower stomatal control and/or higher photosynthetic rates than those in healthy, non-defoliated trees. Seedlings of *P. pinaster* produced larger conduits and higher leaf area than *P. pinea*, expressing higher competitiveness under well-watered conditions. In contrast, *P. pinea* seedlings were more tolerant to water stress and more resistant to xylem cavitation under water stress conditions. A higher capacity of acclimation to water stress in *P. pinea* was expressed by higher xylem plasticity, particularly in tracheid lumen area, than *P. pinaster*. Xylem plasticity was highly correlated to leaves stomatal conductance. In contrast, *P. pinaster* responded to water stress mostly through structural changes at the leaf level. Observed differences in functional plasticity and drought tolerance between the two species agree with ongoing substitution of *P.*

pinaster by *P. pinea* in forests where the two species co-occur. Despite being functionally close, these two conifers may express complementary dynamics in mixed stands under enhanced water stress.

Forgotten giants: Robust climate signal in pollarded trees

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Tree pollarding was one of the most important forest management activities in Europe until the middle of the 20th century. This, almost abandoned, historical management has allowed the trees to maintain great vitality for periods that can exceed the longevity of unintervened trees. In fact, pollards are the oldest trees in many historically humanized areas. Also, this activity has created open agroforest landscapes with a grazing understory where inter-tree competition is low. These characteristics would make pollarded trees to be appropriate for building climate reconstructions. However, pollards have not previously been used for climate reconstruction in dendrochronology since it was assumed that the climate signal of tree rings is disrupted by management disturbances. However, when management activities do not occur simultaneously between the different trees in the chronology, they can be assimilated with the natural disturbances that occur with every other tree. Moreover, since inter-tree competition in pollarded woodlands is low, their climate signals may be more intense than in trees living in dense forests. With this in mind, we have built four tree ring width chronologies of different pollarded woodlands in Central Spain. Our specific hypotheses are: i) tree-ring series of non-synchronously pollarded trees will have a strong climate signal due to reduced inter-tree competition, and ii) since climate is the main environmental signal from residual tree-ring chronologies, chronologies from nearby locations will share a common signal.

We selected four woodlands of old pollarded *Quercus faginea* and *Quercus pyrenaica* trees in northern Spain. We sampled a total of 100 trees per woodland with an increment borer, taking one core per tree. The samples were mounted on wooden supports and sanded with progressively decreasing grit. They were then digitized with CaptuRING[®] and measured with the CooRecorder software. Cross-dating quality was verified using the xDateR app and chronologies were generated using dplR software. Results showed very synchronous growth patterns between individuals with high EPS values. The climatic signal was strong and shared across woodlands. Our results show that the effect of management activities on tree-ring series can be removed with the standardization procedure to retrieve a robust climate signal. The great longevity of pollarded trees and the low inter-tree competition level they face make pollarded trees an extremely valuable source for robust climate reconstructions.

Drought response of silver birch (*Betula pendula* Roth) growing in northern latitudes

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Estimating the response of native tree species to extreme weather events is crucial for developing climate-smart sustainable forestry. However, there are knowledge gaps considering the growth response and how well different tree species are adapted to drought in boreal and hemiboreal regions since extended periods of climatic water shortage were rare in the past. In this study, we aim to assess the drought resilience of silver birch (*Betula pendula* Roth) in Estonia on the example of nine stands of different mean ages (45-110 years) growing on sites of varying fertility and soil moisture status. Silver birch is a pioneer tree species with little demand for site conditions, thus having a wide distribution range, and it is one of the most important broadleaved tree species in the northern latitudes after Scots pine and Norway spruce. We collected increment cores from 104 trees and assessed growth response to recent drought events (1990-2019) identified using climate data and standardized precipitation evaporation index (SPEI), calculated to describe climatic water balance over different periods. We calculated the resilience and resistance index and determined the recovery time of radial growth for these drought events.

Since 1990, one severe (2002, SPEI<-2.0) and five extreme (1995, 1999, 2002, 2006, 2011 and 2018, SPEI<-1.5) drought events have been observed in the region. Preliminary results suggest that the radial growth of studied birch trees was limited by water availability. A positive correlation was detected for summer (June-July) precipitation and monthly SPEI for those months and even stronger for SPEI cumulated over the growing season (6-month SPEI in September). The number of negative pointer years differed among the sites but coincided with drought events or lagged one year. Growth resistance, recovery and resilience varied among the sites and years, but overall growth resistance to water shortage stress was low in the studied birch stands. We observed a considerable decrease in radial increment in drought years and, in several cases, even a year later. Interestingly, the effect of the most severe drought event in 2002 was observed only a year later but not during the drought year. The growth recovery index strongly depended on the calendar year and site and was low for the last two event years (2011 and 2018), when meteorological droughts occurred early in the growing season, decreasing the resilience index.

Complex effect of meteorological conditions on tree-ring width for horse chestnut *Aesculus hippocastanum* in a forest plantation in Latvia

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The shifts in productivity and composition of forests are projected and already ongoing causing ecological and economic consequences. To reduce environmental risks to forest productivity and diversify forest ecosystem services, species introduction is a strategy of climate-smart management; however, this requires knowledge of the climatic sensitivity of trees. Successful introductions mostly benefit from increased yield and low susceptibility to illnesses and pests. However, the latter can be jeopardized by the cointroduction of pests, which can be delayed. Horse chestnut serves as an example in this regard as it suffered an outbreak of the leaf miner moth *Cameraria ohridella*. Horse chestnut is a mesophytic species in its native range and has adapted to a warm, occasionally dry climate. Humidity, notably rainfall in the summer and the coldest months, is the key limiting factor in its native range.

In this work, traditional dendrochronological methods and multiple regression analysis were used to evaluate the sensitivity of the radial increment of horse chestnut growing in a forest plantation in Latvia and its interaction with leaf miner presence. A total of 27 tree-ring time series for a 47-year period were measured, and they were successfully cross-dated. Bootstrapped Pearson correlation analysis was used to screen relationships between the residual chronology of tree-ring width and meteorological variables. Correlation analysis was applied for the common period 1978–2019, as well as for the two sub-periods: 1986–2002 (before leaf miner moth emergence) and 2003–2019 (after).

Radial increment had moderate sensitivity for the common period of 1978–2019, although the samples were representative of environmental signals with trees typically exhibiting comparable patterns of variation. Although the studied horse chestnut was growing under a cold climate (compared to native), the complex effects of summer moisture availability and winter thermal regime were found. Additionally, both direct and carry-over effects of climatic variables on increment were noted. The chronology of tree-ring width showed significant correlations with 13 of the tested meteorological variables, mostly with temperature and precipitation in summer. However, most of these variables were non-stationary and shifts in the interannual variation pattern of tree-ring width occurred before and after the emergence of leaf miners. Furthermore, the strength of the significant correlations increased after the emergence of the leaf miner. The investigated trees preferred

warm, humid summers and warm winters. The estimated weather-growth relationships suggest that increment might favor climate warming, although the emergence of the pest increases the complexity of the relationships, thus rising challenges for growth projections of introduced species, particularly to those previously lacking pests.

Detecting and differentiating disturbance effects by integrating tree-ring width and density data

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Though frequently used for temperature reconstructions, European larch (*Larix decidua* Mill.) is affected every 8–10 years by the occurrence of cyclic larch budmoth (*Zeiraphera griseana*, LBM) mass outbreaks. The resulting growth depressions are unrelated but possibly coinciding with anomalously cold summer temperatures, making precise cause-effect assumptions on interannual timescales challenging. Wood density measurements, however, provide more nuanced pictures that enable temperature- and LBM-induced growth responses to be separated. LBM defoliation events cause sharp density declines in the outbreak year, the earlywood/latewood width ratio differentiates from “normal” years, and the overall growth reduction is usually strongest in the following year and lasts for at least two seasons. Here, we introduce a new detection algorithm that integrates multiple tree-ring parameters in a stepwise procedure. We use total ring width, maximum latewood density, earlywood and latewood width data of seven larch sites from elevational transects in two Swiss valleys where regular LBM activity has been reported for centuries. We compare the results with existing detection methods, including standard deviation thresholds and the *dfoliatR* method incorporating non-host data as well as historical evidence. On this basis, we demonstrate that a multi-parameter approach is a suitable tool to identify different causes for growth disturbances and will help to differentiate LBM events from real cooling events.

Slope exposure effect on tree growth at treeline revisited

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The effect of slope exposure to solar irradiation on treeline tree growth has been repeatedly investigated to explain remarkable differences in treeline elevation between south and north-facing slopes in temperate regions of the Northern Hemisphere. Here we provide comprehensive data ranging from GIS-modelled solar irradiation, through on-site measured soil and air temperatures, wood formation and climate-growth responses for two *Picea abies* sites located on opposite slopes in the similar elevation. The study area is located in the Krkonose Mts. (50N, 15E, Czech Republic) in elevation of 1270 m a.s.l. Data were collected between 2012 and 2016. Our results show that, as expected, total irradiation was systematically higher on south-facing than on north-facing slope. However, the duration of daily insolation was due to local topographical shading longer on north-facing slope than on south-facing slope in the main part of the growing season (DOY 100-DOY 240). Measured air temperatures in tree crowns were higher on south-facing slope with greatest difference in early spring. However, during the growing season, night temperature minima were lower on south-facing slopes leading to similar daily average temperatures between both slope aspects. Soil temperatures reflected total irradiation and were thus generally higher on south-facing slope compared to north-facing slope. However, the greatest and relatively random differences between slopes were observed at the beginning of the growing season when the pattern of soil temperatures was probably influenced by irregular snow distribution. Snow melt indicated by soil temperature was earlier in 2012 and 2013 at north-facing slope and in remaining years (2014-2016) it did not differ significantly between slope aspects. Start of the growing season indicated by first enlarging cells was determined either at same time on both slopes in 2012 and 2014 (DOY 139 and 148 respectively) or earlier in 2013 on north-facing slope. North-facing slope exhibited overall higher cell numbers and wider temporal windows of tracheid maturation which is in agreement with larger trees growing there. Xylogenesis results are corroborated by growth-climate analysis based on site tree-ring chronologies and daily climate data. Both locations showed two important periods for annual ring width – the beginning of the growing season centered around DOY 125 and the peak growing season centered around DOY 180. The temperature-growth correlations were stronger on the north-facing slope. The north-facing slope also exhibited a wider window of growth sensitivity to temperature around peak growing season compared to south-facing slope. To conclude, we

found that for temperate mountains in mid latitudes the factors such as local topographical shading, snow depth patterns and tree age/size are more important for treeline growth rates than slope exposure itself.

Causes of non-stationarity in climate-growth relationships of basal area increments in *Fagus sylvatica* across Europe

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In the course of climate change, forests will increasingly be exposed to climatic conditions outside their historical range. These new conditions will lead to altered growth rates, where forward modelling of secondary growth based on historical climatic conditions offers an invaluable source of information to predict how growth may respond to potential future scenarios. However, this make assumptions on the non-stationarity of the relationship between growth and climate, the underlying causes of which remain uncertain. While temporal variations in environmental conditions can result in non-linear responses of growth to climate, growth trends of basal area increments may itself be a cause of non-stationary climate-growth relationships.

Here, we explore whether growth trends of basal area increments in *Fagus sylvatica* (European beech) has an influence on its climate sensitivity and how they relate to differences in physiological and environmental factors. We further nuance this with interacting effects of climatic conditions. To establish robust links of causation, multiple methods of analyses are applied on a European-wide dataset.

Preliminary results show strong differences in climate sensitivity of secondary growth, i.e. non-stationarity, depending on both growth trend and climatic conditions. Weakest climate sensitivity was found for juvenile sites with increasing growth trends, likely mediated the protection from ambient environment by growing in the understory. While declining growth trends, which are often assumed to be caused by stress, showed tighter climate sensitivity, they were still considerably lower than those of sites without clear increasing or decreasing trends, which in turn are likely related to mature and dominant trees. Further, these differences were clearer during dry years, whereas they partly disappeared or weakened during wet years.

Our results show that climate-growth relationships are non-stationary depending on both climatic conditions and factors relating to age and structure. Incorporating this knowledge can both improve the predictions of forward modelling secondary growth and lead to better understanding of how to manage European beech forests in a changing climate.

Assesment of the relation between cellulose and lignin in the annual rings of *Pinus pinea* micro-cores – first results

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Trees are well-adapted organisms to the environment, being able to change their growth and defence strategies (i.e. competition for light and fight against pathogens) depending on the site/climatic conditions. What makes trees such robust organisms? Cell walls (CW) and their chemistry are at the base of their strategy. CWs are constituted mainly by two polymers as structural components: cellulose and lignin; each playing an important role in plant growth and survival. Cellulose is the base of the CW, is a simple polymer made by the repetition of cellobiose; on the opposite, lignin provides structural support to the cells, contributing to the water transport, acting as a physical barrier against pathogens, thus is a complex polymer made of different monomers varying its composition between species and between plant tissues (e.g. wood, bark). Plants can produce tailor-made lignin according to needs in response to environmental conditions. Consequently, the regulation of lignin biosynthesis is a complex process, far from being fully understood, despite the efforts made. From the physiological point of view, plant development needs to make trade-offs between growth and strength/defence, i.e production of cellulose (tree growth) vs. lignin (strength). The relation between cellulose and lignin in stem wood has been explored due to the commercial valorization of wood. However, as far as we know, this relation has not yet been made in annual rings. The study aimed to determine this relation over the years and compare them with ring width values (RW). The preliminary study started with a collection of radial micro-cores from *Pinus pinea* littoral forest in Remolar, Barcelona. Two trees were selected to collect rings from 2012 to 2021. RW values were measured, and rings were separated. Each ring was extracted with dichloromethane, ethanol and water in the Soxhlet apparatus for 8h for each solvent to remove extractives. Analytically, from pyrolysis we attained the quantification of lignin and carbohydrates (cellulose and hemicelluloses). About 0.15 mg of each ring was pyrolysed at 550°C (1 min) in CDS pyroprobe, and the volatiles separated in a gas chromatograph linked to the mass spectrometer for identification. The relative composition of total carbohydrates (TC) and total lignin (TL) were determined, and the ratio C/L was calculated. Following the literature, TL ranged from 22.4 to 30.6% (total pyrogram area, TPA).

Since pine is a softwood, the lignin only presented compounds of H- and G-units, with the prevalence of G-units (19.6-28.3% of TPA). TC ranged from 48.0 to 60.2% (% TPA). As expected, the C/L ratio was always higher than 1 (1.57 to 2.54), reaching 2.54 in 2020, characterized by high precipitation (1012.5 mm), producing more cellulose and less lignin. These preliminary results revealed a linear but negative correlation between TL and TC ($TL = -0.358 TC + 46.7$; $R^2=0.171$). This phenomenon was also mentioned in the literature on aspen stem wood. RW present a linear but negative correlation with TL ($RW = -0.046 TL + 2.23$; $R^2=0.135$), contrasting with a positive correlation using TC ($RW = 0.175 TC - 6.02$; $R^2=0.051$). More data are being collected and processed to validate these models and hopefully increase their robustness. Our main goal is to contribute to increasing knowledge about how plants react to the environment throughout the production of cellulose and lignin as their main constituents. Besides, this information may also help researchers understand the influence of climatic changes on wood formation, which is the key factor for wood valorization.

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Tree-ring chronology in the subalpine belt of the southeastern Dinaric Mountain of Austrian pine (*Pinus nigra* J.F. Arnold) and bosnian pine (*Pinus heldreichii* H. Christ)

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The best preserved black pine (*Pinus nigra* J.F. Arnold) primeval forests and bosnian pine (*Pinus heldreichii* H. Christ) primeval forests we find in the subalpine belt of the Dinaric mountains in Bosnia and Herzegovina, Montenegro and Republic of North Macedonia. Tree-ring data from locations where trees are particularly sensitive to variation in temperature or precipitation are among the most important sources of proxy climate data. Our study area is located on the Orjen mountain in the Bosnia and Herzegovina and Montenegro where is located primeval forest of bosnian pine and in the mountain Maglic in the Bosnia and Herzegovina where is located primeval forests of black pine. The climate in the southeastern Dinaric mountains is typical for mountains region and is strongly influenced by Mediterranean climate and humidity.

Old trees with healthy trunks were selected for sampling. Two cores from opposite side, and perpendicular to the slope were taken from each tree. Samples were scanned using ATRICS system, further processing of data was done by TSAP-Win™ program and controlled by program COFECHA. That steps were used to build sites chronology and regional chronology. The reconstruction of the dynamics of natural disturbances was made for each site separately using percentage methods. Standard chronologies for each site were compared with mean monthly temperatures and the monthly sum of precipitation from the previous September to the current October for the 1951–2009 period in order to detect potential differences in trees' response to climate at different sites. Climate data for building chronologies for our localities was taken from KNMI Climate Explorer.

We constructed 605-year long *Pinus heldreichii* chronology and 397-year long *Pinus nigra* chronology. Reliable chronology for climate reconstruction for *Pinus heldreichii* is from 1697 to 2016 (according to EPS 0,85) and for *Pinus nigra* is from 1675 to 2016 (according to EPS 0,85). According to climate correlations strong relationship was found between tree-ring indices and precipitation from September of the previous year and June-July of the current year for the both tree species. Negative impact of temperature from August and September of the previous year and from July and August of the current year was detected for the *Pinus nigra* from Perucica while for *Pinus heldreichii* from Orjen temperature from Jun of the current year showed negative impact.

How plastic are the weather-growth responses of eastern Baltic Scots pine?

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The anticipated climatic changes are expected to decrease abundance of Scots pine in the eastern Baltic region, which, considering the economic and ecological importance of the species, are expected to have substantial socioeconomic consequences. Such predictions are presuming linear responses to environment, which, however, is true only under a limited part of environmental gradient. Also, populations of widely distributed species can differ in sensitivity, thus implying varying degree of plasticity of response to changing environments. Hence, assessment of regional weather-growth response and their plasticity is necessary for more reliable projections. Regional weather-growth responses were assessed based on the tree-ring width measured for 20 commercial stands spreading from southern Finland to northern Germany. Correlation analysis was performed to estimate the local relationships, and mixed generalized additive model was used to assess such relationships at the regional scale. Across the studied climatic gradient, the weather-growth correlations showed a southward shift of limiting conditions from growing season temperature in the north to drought related variables in the south. However, there was quite a high variability among the stands within the gradient. The regional responses were mostly nonlinear indicating presence of threshold values for responsiveness or showed presence of optima. Regional responses indicated that tree-ring width of Scots pine was controlled by a complex of meteorological conditions including temperature and precipitation in winter and summer, as well as the conditions in the late summer of preceding year. To assess the degree of local adaptation and plasticity of weather-growth response of eastern Baltic population of Scots pine, material from five parallel provenance trials within the study region was analysed. Provenances differing by field performance were selected to estimate the sensitivity-productivity relationships. The regional generalization of the weather-growth relationships revealed productivity-sensitivity tradeoffs, which however, differed by underlying meteorological conditions. In contrast to the expected, the top-performing provenances were more sensitive to summer moisture regime implying that higher plasticity of resource allocation as an adaptation to water shortage. The low-performing provenances, however, were more sensitive to preceding conditions, thus indicating higher dependence on nutrient reserves, and hence more conservative growth strategy, which appears as a maladaptation under increasing environmental variability under hemiboreal conditions.

Silver birch – ecologically plastic, yet weather sensitive

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In Europe, Silver birch (*Betula pendula* Roth.) is being advocated as an alternative for commercial forestry aiding sustainability of forests under increasing variability of meteorological conditions, presuming high plasticity of growth responses. Still, due to limited studies with scattered spatial cover, weather sensitivity of growth of silver birch is largely unknown. As for widespread species, local populations of silver birch can be genetically adapted to local conditions implying specific weather sensitivity of growth. Furthermore, ecological response across environmental gradients are bell shaped, while close-to-linear responses can be evident on limited part of the gradient, hence they cannot be widely extrapolated. This highlights the relevance of assessment of growth responses across considerable part of climatic, rather than spatial gradient. In total, 21 naturally regenerated and conventionally managed stands of silver birch located from northern Germany to southern Finland were sampled and within each 10–15 trees were cored, collecting two cores per stem. To measure tree-ring width, thin cross-sections were cut using WSL core microtome and double stand in Astra blue and safranin to increase the contrast between earlywood and latewood, thus allowing recognition of tree-ring borders, including those in years with suppressed growth. Residual chronologies for stands were calculated to estimate weather-growth relationships. At local level these relationships were screened using a bootstrapped Pearson correlation analysis (presuming linear relationships), while at regional level these. At the regional level, weather-growth relationships were generalized using mixed generalized additive model, which allows estimation of nonlinear responses based on heterogeneric ecological data. Correlation analysis indicated spatial gradient of weather growth correlations as growth limitation shifted from temperature during the dormancy to water availability during vegetation period in southern Finland and northern Germany, respectively. The regional weather-growth responses were mostly nonlinear, revealing thresholds of sensitivity or presence of optimum conditions, which adheres to the bell-shaped nature of ecological responses. These responses also were stationary, as spatiotemporal differences were accounted during the modeling by inclusion of random effects. At the regional scale, drought related variables were the main drivers of increment and winter conditions related to soil temperature had a secondary role. Summer temperature had some carryover effects. Based on the estimated responses, increased variability of increment of silver birch is expected under changing climate; still, sensitivity and plasticity of increment can also be considered as an adaptation to shifting environments.

***Betula nana*: tree ring chronologies at its southern range border**

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Climate change has caused dramatic changes in tree distributions and growth. Among such studies in Northern regions, climate change induced variation of *Betula nana* has been described. As Latvia is at the southern range of *Betula nana*, it is a protected species. Our aim is to analyse tree-ring growth dynamics in relation to climatic factors for *Betula nana* along a North-South gradient in Latvia. In five miles along a North-South gradient in eastern Latvia, five plants were collected in each habitat where found (bog, transition mire and swamp). Length of segments of each individual was measured and morphological characteristics were described. Cross-sections were obtained at ten centimeters intervals along the main branch of each plant. The discs were then stained, and tree-rings were measured and visually cross-dated. In general, the growth morphology and chronologies were similar along the North-South gradient but differed between habitats. There is a significant difference in cambium activity between the upper part of the main branch and the lower parts that had senesced. The effect of climate was mainly local and was evident using correlation between climate and chronologies divided in time periods. However, we found a significant correlation between average air temperature in time periods, which differed along a North-South gradient.

Future research on understanding better the growth of *Betula nana* should include sampling sites in Northern regions with the same methods. Pointer years should be analysed, as well as their correlation with climate change.

Comparing the effect of artificial drought and crown reduction on tree ring response in sessile oak and Norway spruce seedlings

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Extreme climatic events such as hotter drought, compounded by biotic stressors, cause much of the forest mortality observed worldwide. Following extensive deforestation, it is essential to have robust regeneration material that can withstand the initial establishment shock and effectively restore the area. In this study, we investigated how the tree-ring anatomy of young seedlings responds to treatments that are intended to improve their fitness and increase their chance of survival under field conditions with limited soil water availability. Two widespread and economically important tree species with distinct anatomies, specifically sessile oak (ring-porous) and Norway spruce (conifer), were selected for this investigation. We treated 3-year-old plants with 50% crown reduction (CR) and hydrogel (H) application in soil, and followed their development in dry and wet conditions over a two-year period (2021-2022). We hypothesized that both CR and H application would have a beneficial or ameliorative effect on radial increment under dry conditions. Therefore, our aim was to test whether these modifications would lead to xylem adjustments that specifically support plant growth. The most recent two rings were evaluated to assess changes in wood structure by analyzing various xylem traits in the stem transverse section. Our preliminary results revealed distinct adjustments in wood anatomy of these two species. Regardless of the treatment, sessile oak exhibited a marked decrease in tree-ring growth under dry conditions, whereas hydraulic conductivity increased in all treatments, except CR. This implies the enhanced ability to transport water more efficiently. On the other hand, the tree-ring growth of Norway spruce responded positively to CR, as no notable decrease was observed under dry conditions. In wet conditions, radial cell wall thickness and radial tracheid diameter were positively impacted by both CR and H only in earlywood tracheids. This suggests contrasting biomass allocation patterns in the two species. Sessile oak appears better able to adjust its biomass partitioning to resource availability. However, confirmation of this would require additional research on the belowground components. Conversely, Norway spruce seedlings exhibit a greater response to treatments intended to facilitate their growth and development during the initial stages of their development.

Analysing the ups and downs: The effect of local parameters on Norway spruce within and between plots.

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During the last century Norway spruce (*Picea abies* L Karst) has spread within and beyond its native distribution in Europe. As summer droughts and water scarcity become increasingly common, the drought sensitive Norway spruce is facing new difficulties, especially in widespread monocultures. Thus, the need to adapt to the changing climate is acute.

The rapid change of climate emphasizes the importance of both plot and local level parameters when examining the connection between the yearly radial growth response to climate and drought. Even when situated close to one another, not all trees react to climate synchronously. We use parameters like slope and aspect both within and between plots to analyse the growth response and to subgroup the trees according to the characterising common parameter.

Collecting detailed data is important to understand why some trees share growth characteristics despite being further apart and why others don't, even though they are close to each other. We sampled approximately 60 trees (>5 cm DBH) per plot and took two cores per tree. All trees, living or dead, as well as stumps and fallen trees within the plot are mapped from a centre point with an accuracy of 10 cm and the bearing was recorded in order to situate all trees precisely. With these measurements we can present the plot in a xyz- coordinate system and create high resolution local digital elevation model.

With these plot settings we analyse, within a regression framework, parameters like slope and aspect within and between plots in Berchtesgaden in Bavaria, Germany and in Mercantour in southern France.

Radial growth comparison between *Pinus sylvestris* and *Juniperus spp.* shrubs from northern Scandinavia

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Trees and shrubs are among the most sensitive elements of the environment, especially at the northern latitudes. For a long time, trees have been recognized as a valuable source of information on environmental conditions in northern Scandinavia. Shrubs also grow there, but they are less studied than trees. Moreover, we lack comparison growth ring studies between trees and shrubs from the same habitat. For this purpose, we aim to characterize the coherence in the radial growth pattern between the two woody plant species i.e., *Pinus sylvestris* trees and *Juniperus spp.* shrubs. The study area is located in Øvre Pasvik, NE Norway. We analyzed 20 samples of each species within the same habitat, i.e., at a maximum distance of 300 m. We identified negative and positive pointer years in both chronologies. In addition, we determined radial growth and wood anatomical changes in both tree and shrub growth rings. We specifically focused on frost rings, missing rings, and growth suppressions. In our study we identified radial growth and wood anatomical changes in both species in the last 150 years. Comparison studies between trees and shrubs have potential to broaden our understanding on woody plants sensitivity to changing environmental conditions in northern latitudes.

Climate-growth relations along an elevation gradient in the Italian Alps: additional insights from dendrometer data

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To predict the impact of climate change on forest ecosystems a detailed knowledge on the influence of weather and climate conditions on tree growth is important. While classic tree ring width analysis has the advantage of providing a look back into the past, its temporal resolution is usually limited to two points (early wood and late wood) per year. Automatic dendrometers provide tree growth data with a sub-daily temporal resolution as well as information on the tree water status that can provide additional insight into climate-growth relations. At the LTSER site Matsch|Mazia in the Italian Alps we started radial growth measurements with band dendrometers (DR26/DRL26, EMS Brno) at five sites along an elevation gradient from 1160 to 2100 m a.s.l. for *Larix decidua* and at two sites at 2000 and 2100 m a.s.l. for *Pinus cembra* in 2012. In 2015, we added two forest line sites at 2250 m a.s.l. (*Larix decidua*, south slope) and 2320 m a.s.l. (*Pinus cembra*, north slope) and in 2017 a *Pinus nigra* site at 1160 m a.s.l. Four trees were measured per site and species. For all sites we also analysed tree ring widths from 10 to 15 trees per site and species and correlated them with long-term (since 1865) temperature and precipitation records. We found clear differences in yearly growth of *Larix decidua* along the elevation gradient in dry years when limited water availability led to an early cessation of growth at lower elevations. In contrast hardly any difference in yearly growth with elevation was observed in more humid years. This corresponds well to positive growth responses to precipitation found in tree ring data for *Larix* at low elevation. We also found consistent higher yearly growth in *Larix* than in *Pinus cembra* at high elevation sites as well as in *Pinus nigra* at low elevation. At high elevation *Pinus cembra* growth was limited stronger by air vapour pressure deficit (VPD) than *Larix*, while in tree ring data no water limitation was indicated by a positive precipitation response for neither species. At low elevation, a stronger sensitivity of *Pinus nigra* to VPD and/or soil moisture availability could be the reason for lower yearly growth than in *Larix*. Overall our dendrometer measurements provided some valuable additional information to explain observed tree growth patterns.

REMOVED LAST MINUTE

The thicker active layer and extreme climatic conditions affect the growth of *Salix helvetica* in the highest site in the Alps (Gornergrat, Pennine Alps)

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Swiss willow (*Salix helvetica*) is high mountain species with an altitude range, as reported in the literature, 1,700 - 2,700 m a.s.l., growing up to 50cm tall. Near the upper limit of growth, the shrub is creeping, tightly attached to the ground, and rooted in debris or rock crevices. On the southern slope of the Gornergrat ridge (Pennine Alps, Switzerland), specimens of Swiss willow were found at an altitude of 2,950-3,000 m a.s.l., one of the highest locations of the range of this species. Dwarf shrubs, growing above the upper forest limit or in the Arctic areas, are very sensitive to changes in the natural environment and are an excellent bioindicator of climatic, ecological, and geomorphological processes. Taking this into account, the main research questions we examine are: (1) Can data from *Salix helvetica* growing in the highest altitude range be used to dendrochronological analyses and to detect extreme climate conditions? and if yes, (2) Is the increase in the thickness of the permafrost active layer reflected in the growth-ring width and main anatomical traits? To answer the research questions, we used dendrochronological, meteorological, and permafrost data. In total 19 samples of *S. helvetica* were collected in Gornergrat rocky ridge in autumn 2022. The samples were processed according to the dendrochronological protocol used for the preparation of wood samples with very small growth rates to measure the growth-ring width. Based on image quality and correlation with the master chronology, we selected 6 individuals for QWA analyses. Permafrost data were obtained from PERMOS database for two boreholes at Stockhorn STO_6000 and STO_6100, located at an altitude of 3,400 m west of the Gornergrat culmination. The age of the sampled shrubs reaches a maximum of 70 years. A very large variation in the growth-ring widths and the size of the vessels can be observed in anatomical structure. The chronology time span covers 1958 - 2022. The first results show a high correlation between extreme climatic events (e.g. droughts) and the growth-ring width. The observed increase in the thickness of the active layer at Stockhorn, which has almost doubled

in the last 20 years of observations, may have influenced the increase in soil drought. Significant fluctuations in the growth-ring width and the size of the vessel are observed during the last decade.

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Dendrochronology of *Rhododendron myrtifolium* from the high alpine site in the Eastern Carpathians, Ukraine

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Rhododendron myrtifolium Sehot & Kotsehy is a high-mountain endemic plant growing at several localities in isolated massifs of the Eastern Carpathians and in the Balkan mountains. One of the greatest numbers of localities of *R. myrtifolium* can be found in Chornohora - the highest mountain range in Ukraine and the Outer Eastern Carpathians. *R. myrtifolium* grows here in subalpine and alpine belts at the elevation between 1,500 and 1,900 m a.s.l., reaching the uppermost position at 2,030 m a.s.l. on Hoverla Mt (2,061 m a.s.l.). This plant often forms community composed of other species from the Ericaceae family. Plant height does not exceed 30 cm. The aim of the study is to assess the potential of this species in dendrochronological research as an important indicator of modern environmental changes in the high mountain zone of the Carpathians. 12 specimens were collected from the eastern and south-eastern slopes from an altitude of 1,950 - 2,000 m a.s.l. on Hoverla Mt. In addition, 40 cores were taken from fir trees growing at an altitude of 800 - 1,000 m a.s.l. for comparison of climate signal. The samples of *R. myrtifolium* were processed according to the dendrochronological protocol used for the preparation of wood samples with very small growth rates, to measure the growth-ring width and analyze the main anatomical features. The oldest specimens were 65 years old. There is a very wide variation in the width of the annual growth, from very wide, exceeding 300 μm , to very narrow, less than 40 μm . The results show a significant correlation with summer precipitation. The worsening of growth conditions, marked by narrow rings in recent years, should be linked to the increasing impact of drought stress.

Dendroclimatology in the Azores: starting to fill the gap

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Dendrochronological studies are scarcer in areas with high relative humidity, low thermal amplitude and without a very pronounced climatic seasonality, such as the Azores Islands. Hence, this knowledge gap extends to the native and endemic Azorean tree species, for which almost no tree ring research was available, despite the available knowledge about their ecological amplitudes, occurrences, and potential distribution. To start fulfilling this gap, more than 900 wood cores were collected in this work from three Azorean endemic woody species: *Juniperus brevifolia* (Seub.) Antoine (Cupressaceae), *Ilex azorica* Gand. (Aquifoliaceae) and *Laurus azorica* (Seub.) Franco (Lauraceae). Ten different stands were sampled at two islands from the archipelago, applying standard dendrochronological and dendroclimatic methods, including crossdating, detrending, and the exclusion of samples or chronology portions, due to tree ring anomalies or to low sampling depth. Likewise, several modelling options were used, such as Pearson correlation, Generalized Linear Models and Random Forest, to determine the most relevant climatic drivers of tree growth. Although the three species showed some partially indistinct ring boundaries and wedging rings, globally, the samples are considered as adequate for dendrochronological research. A clear separation between a yellowish sapwood and the reddish-brown heartwood was found in *J. brevifolia*. For *I. azorica*, a layer of vessels associated to the ring boundary was found in most growth rings. Both the shortest and longest chronologies were found for *I. azorica*, respectively in Sete Cidades with a length of 47 years and in Terra Brava with a length of 128 years. Diverse relations between tree growth and temperatures were found, mainly a positive effect of spring temperature (*I. azorica* and *L. azorica*) and a negative effect of summer temperatures (all three species). Precipitation also affected tree radial growth, especially the positive effect of spring precipitation (*I. azorica*).

Additionally, previous year climate was also relevant on tree growth in *I. azorica* and *L. azorica*, indicating lagged physiological effects. In the Azores, limitations in dendrochronological studies are related to the low thermal amplitude, to the absence of a pronounced climatic seasonality, and to the high within stand variation in tree ring patterns. Moreover, the high variability found between stands is likely related to natural (e.g., elevation, terrain and soil differences, succession and regeneration processes) or anthropogenic disturbance (e.g, tree cutting, plantation and spread of exotic species), thereby contributing for a considerable variation in chronology length and to slightly different climate-growth relationships at different sites. The temperature signal found in climate-growth relationships raises concern, because summer temperatures are expected to increase, which could lead to local extinctions. Likewise, this approach, complemented with other radial growth proxies and the use of dendrometers, could be extended to other native species with lower elevation distribution ranges, such as *Morella faya* Aiton (Myricaceae) and *Picconia azorica* (Tutin) Knobl. (Oleaceae), or to exotic species, such as *Cryptomeria japonica* (L.f.) D. Don (Cupressaceae) and tree species already studied in temperate Europe. Additionally, a global analysis of the entire dataset, exploring different detrending and modeling methods could also be undertaken, providing hints for a comprehensive methodology suitable for the region.

Dendroecological analyses for olive cultivar characterization

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Due to global warming, a significant increase in frequency and severity of drought episodes is predicted in the Mediterranean Region. Olive (*Olea europaea* L.) is a relatively drought-tolerant tree species cultivated in Mediterranean region. However, prolonged hot and dry summer can induce hydraulic stress, leading to fruit yield reduction. Hence, studies about the adaptation and tolerance of olive trees to stress are fundamental to better understand how different cultivars will cope with ongoing climate change. Mature trees of two high-quality cultivars (Moraiolo and Maurino), growing in Central Italy, were selected to evaluate differences in growth, fruit production, and tolerance to hot and dry conditions.

To study Intra and inter-annual physiological responses (stomatal sensitivity, photosynthetic capacity and intrinsic water-use efficiency) to local climate, carbon and oxygen stable isotopes were investigated in tree rings of two olive cultivars during three growing seasons of 2020, 2021 and 2022. The two cultivars differed in seasonal $\delta^{13}\text{C}$ trends during the three years. Tree ring $\delta^{13}\text{C}$ values increased during earlywood formation and decreased in the latewood.

The increasing trend in $\delta^{13}\text{C}$, from early spring to summer indicates a decrease in photosynthetic isotopic discrimination. This would imply an increase in intrinsic water-use efficiency in response to increasing temperature and decreasing water availability. In this regard, cv. Maurino showed a more limited range of variation in comparison to cv. Moraiolo. This may be related to different stomatal sensitivity, leading to more limited stress tolerance in Maurino with respect to Moraiolo. In all the years, Moraiolo reached significantly lower $\delta^{13}\text{C}$ values in the winter and higher $\delta^{13}\text{C}$ values in the summer, indicating a higher stomatal responsiveness and a higher phenotypic plasticity in response to changes in environmental conditions during the vegetative and reproductive season. In agreement with this hypothesis, the $\delta^{18}\text{O}$ values of the 3-year-old branches were significantly higher in trees from Maurino, suggesting higher transpiration rates.

Hence, Moraiolo cultivar has the potential to better tolerate thermal variations and drought conditions in response to Mediterranean climate change.

Unveiling willow biomass trends in ice-free Greenland through dendroecological and remote sensing time-series

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The Arctic region's potential to increase the terrestrial carbon (C) sink due to enhanced plant growth from recent climate change is an important feedback mechanism on the global C cycle. To better understand, this phenomenon, we studied two closely related willow species, *Salix arctica* Pall. and *Salix glauca* L., by measuring 234 growth ring time-series and basal diameters at harvest from 20 sites across ice-free Greenland. We combined our findings with remote sensing observations to better understand ongoing and future changes in above-ground C in the region. Our research spanned the climatic sub-zones of the Arctic, from the low Arctic to the extreme northernmost High Arctic. Across Greenland, temperature significantly predicted shrub growth at eight sites. Biomass data from two of the sites helped us establish an allometric relationship between willow basal diameter and individual above-ground biomass (AGB) with good predictive power. By comparing cumulative shrub biomass at the site level with Landsat pixel Normalized Difference Vegetation Index (NDVI) values for the sites, we were able to estimate changes in shrub biomass over time. While we observed increases in estimated shrub biomass in the recent decades at some sites, others showed no change despite similar rates of warming. Our results demonstrate that warming leads to different magnitudes of growth and biomass change depending on local and regional environmental variation that is not related to differences in temperature per se.

Scots pine growth and climatic sensitivity in Chernobyl exclusion zone

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The Chernobyl accident on 26 April 1986, caused tree death near the nuclear power plant and affected forest ecosystems throughout the Chernobyl exclusion zone. Thirty years after the accident, the radiation continues to exert its disastrous effects on the surviving trees. However, the extent to which continuous exposure to radiation over several decades has affected the radial growth of trees and their sensitivity to climate variability remains poorly understood.

In this study, we used common dendrochronological approaches to investigate Scots pine trees' radial growth and its sensitivity to climatic variables, i.e. air temperature, amount of precipitation, and drought, in two stands that received sub-lethal and moderate radiation doses after the Chernobyl accident. To track changes in radial growth, we performed a pointer-year analysis using two techniques - normalization in a moving window and the bias-adjusted standardized growth change. To assess the growth-to-climate relationship, we used the double-moving window approach. Additionally, to evaluate the differences in these relationships between the two study stands, we applied the Full-Duration at Half-Maximum method FDHM. The effects of drought episodes were evaluated using growth resistance and recovery indices.

The stand exposed to sub-lethal radiation dose shows a significant reduction in radial growth in 1986 with a deflection period of one year. In contrast, the stand exposed to moderate dose of radiation demonstrates no significant decrease in growth either in 1986 or in subsequent years. The use of the moving response function and FDHM allowed us to detect several mutual patterns in the growth-to-climate relationships unrelated to the Chernobyl accident. Thus, the results of the study indicate that the sub-lethal radiation dose had a dual effect on the trees: it

reduced their radial growth and jeopardized the physiological ability of the trees to respond to the extreme spring and summer drought in the year of the accident.

In conclusion, our results suggest a non-specific growth response to radioactive contamination and emphasize the need for reliable indicators, particularly at the level of wood anatomy.

Imprints of volcanic degassing in tree rings at the Laacher See, Germany

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Once the setting of central Europe's largest Late Pleistocene volcanic eruption, the Laacher See in the East Eifel of Germany is still subject to an active volcanic field. The system continuously emits magmatic carbon dioxide (CO₂) through numerous mofettes flanking the shoreline and exposing the overlying ecosystems to elevated and depleted CO₂. We here investigate the spatiotemporal influence of volcanic CO₂ degassing on local beech (*Fagus sylvatica*) and oak (*Quercus robur*) trees by performing tree-ring width, stable carbon isotope, radiocarbon, and chemical composition analyses. Despite some interesting features in the studied proxy data that require further investigations, initial results indicate no impact of volcanic degassing on our diagnostics considering directly exposed and unexposed reference samples. Findings from this approach are expected to support assessments of the potential impacts of magmatic CO₂ emissions on surrounding vegetation.

Unravel the metabolic drivers of ^2H fractionation in plant carbohydrates to enable the triple isotope ($^2\text{H}/^{18}\text{O}/^{13}\text{C}$) approach for tree-ring research

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In recent years, it became clear that the hydrogen isotope composition ($\delta^2\text{H}$) of tree-ring cellulose carries much information on a tree's physiology, such as the internal carbohydrate dynamics, rather than merely on the isotope composition of source water. New methodological achievements enable high-throughput measurements of the $\delta^2\text{H}$ of non-structural carbohydrates (NSC; sugar and starch). With these, we can now analyse a great number of samples as needed to disentangle the metabolic processes responsible for the variation of $\delta^2\text{H}$ in tree-ring cellulose. However, a mechanistic understanding of the metabolic and physiological processes underlying the ^2H fractionation and how these processes differ from the ^{18}O and ^{13}C fractionation is still lacking. Therefore, we conducted two climate chamber experiments to test a novel triple isotope approach:

To study the initial leaf-level ^2H fractionation processes during carbohydrate assimilation, we grew seven plant species (*Quercus pubescens*, *Phytolacca dioica*, *Oryza sativa*, *Hordeum vulgare*, *Solanum cheesmanii*, *Salvia hispanica*, *Sorghum bicolor*) at different temperatures (ranging from 10 to 40 °C in 5 °C steps) with a constant vapour pressure deficit (VPD). Subsequently, we collected leaves for isotope measurements of leaf water and sugar and conducted plant physiological measurements such as assimilation and respiration rate. To investigate how the $\delta^2\text{H}$ of fresh assimilates is imprinted onto tree-ring cellulose and how climatic conditions influence these processes, we grew five tree species (*Larix decidua*, *Pseudotsuga menziesii*, *Fagus sylvatica*, *Quercus pubescens*, and *Quercus ilex*) in six climate chambers where we tested the impact of temperature, VPD, and drought using a fractional factorial design.

Our results demonstrate that plant's photosynthesis and respiration are counteracting ^2H fractionation processes. While photosynthesis is generating ^2H depleted sugar, respiration is enriching the sugar pool with ^2H . The measured $\delta^2\text{H}$ of leaf sugar reflects the combination of these two effects, whereas in heterotrophic tissues, solely the respiratory ^2H enriching

processes remain. Thus, both a reduced CO₂ fixation rate and an increased respiration rate can lead to a ²H enrichment of the sugar pool, eventually leading to higher δ²H in tree-ring cellulose. This enrichment increases with the increase of temperature, VPD or soil drought. On the other hand, δ¹⁸O of leaf sugar and tree-ring cellulose are reflecting the δ¹⁸O of leaf water, and δ¹³C the leaf level gas exchange. By combining δ²H, δ¹⁸O, and δ¹³C, we identified which of the climatic drivers is responsible for the ²H enrichment in the tree-ring cellulose.

We conclude that the novel triple isotope approach can strongly improve the tree physiological and climate reconstructions using tree rings.

Climate-growth relationships of quaking aspen (*Populus tremuloides*) in Great Basin, western United States

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The Great Basin is an important physiographic region located in the interior of the western USA. While covering an extensive spatial area, only a small portion of the Great Basin is forested, and at higher elevation those forested areas include quaking aspen (*Populus tremuloides* Michx.). Quaking aspen is the most geographically widespread deciduous tree species in North America. In the western US, quaking aspen are the dominant hardwood forest type of the montane zone. Aspen forests harbor disproportionately high biodiversity and ecosystem functions compared to their modest areal extent. In this study we analyzed quaking aspen tree-ring data from 20 locations across three mountain ranges in the northern Great Basin to assess the relative vulnerability of this species to ongoing climate change and to elucidate the most important drivers of growth. We expected that growth variability would be strongly controlled by moisture availability in the generally arid Great Basin. Tree-ring data were processed by standard dendrochronological procedures (i.e. cross-dating, detrending, chronology building) to develop 20 plot-level chronologies and three master chronologies representing each of the individual mountain ranges. We then computed bootstrapped correlations between monthly resolved climate data (average temperature, precipitation, and climate moisture index) and the residual tree-ring chronologies. Correlations coefficients were calculated monthly starting from the growing season of the previous year through the end of the growing season the year of tree ring formation (i.e., previous year June to the current year September), seasonally (previous year September to current year February, current year March to May, current year June to August) and for the water year (previous year October to current year September). To assess whether the relationships were stable over time, we calculated 20-year moving correlations overlapping by one year. Our results indicate that variability in tree growth for a given year is primarily driven by moisture availability in the preceding winter season (i.e., previous September to current February) and secondarily by the current year spring and summer months (i.e., April to August). Furthermore, spring temperature had a positive effect on growth in some plots and mountain ranges. Quaking

aspen growth-climate sensitivity varied both between individual mountain ranges and between plots within mountain ranges. These differences were mainly explained by plot-specific climate conditions, with higher growth sensitivity to moisture availability in plots located in drier environments, and lower sensitivity to moisture in relatively wetter locations, where growth was also often positively affected by spring temperatures. Interestingly, we did not find an increase in sensitivity to moisture availability in the recent portions of the tree-growth chronologies (i.e., after 1990s). The combination of stable sensitivity and large variability in aspen growth responses to climate suggests that multiple resilience pathways may exist for quaking aspen in the Great Basin in the face of anticipated drought related to climate change.

Climate response shift within the largest *Pinus Cembra* populations in Romania

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Environmental conditions influence tree ring growth and consequently wood density. As extreme climatic events are becoming more frequent, this may threaten forest ecosystems worldwide. Thus, investigating wood species growing in temperature-limited environments is becoming essential in understanding the effect of climate change on trees as they experience these climate changes at a faster rate. This study aimed to explore the inter- and intra-annual variability of ring width and maximum density of the high-altitude *Pinus cembra* L. and to assess correlations with climate conditions. The samples were collected from two locations of its eastern distributional range: South-West (Retezat) and Nord-East (Călimani) Romania. Specifically, we analyzed tree ring-width (TRW) and maximum density (MXD) time series and assessed the correlation with monthly and daily climate data in mature trees over the last century (1900-2015). The analysis showed similar results between the two sites, with TRW being less sensitive to climate especially within Retezat stone pine population compared to MXD which showed stronger correlations with climate, above all with temperature. The temporal stability of the climate-growth relationship highlighted an inversion of the correlation in the second half of the century. This may be caused by the better-growing conditions given by raising temperatures which may cause an upward shift of the vegetation belt. These findings stimulate new questions, including the need to understand the impact of climate variability on the anatomical structure of *Pinus cembra* to better understand species reaction and distribution under future climatic conditions.

Trends in changes of stem basal area between 1990 and 2015 across environmental gradients and five main tree species in Central Europe

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With climate warming, the optimal growth conditions of temperate tree species are expected to shift to a higher elevation where the growth increases are not limited by excessive drought effects. Changes in stem biomass can be precisely determined using permanent plots with repeated measurements. However, such measurements are demanding and a network of permanent plots usually consists only of tens of plots hardly covering wide environmental gradients. To overcome this problem, we employed a tree-ring database (www.treedataclim.cz) with >1000 sites and >26 000 trees and calculated for each site mean stem basal area. We created two artificial datasets, the first contains series with the last year in 2015 ("2015 dataset"), the second involves series with the last year in 1990 ("1990 dataset"). We further adapt datasets to contain series with identical age composition by removing old samples from "2015 dataset" and by truncation all series in 1990 and removing young samples in "1990 dataset". Both data sets contain trees with ages between 50 and 150 years and mimic the situation of repeated measurements at permanent plots in 1990 and then again in 2015. We also accounted for age trend in the stem basal area of plots differing in stand age. We then tested for differences in stem basal area between 1990 and 2015 and inspect trends in stem basal area changes along the elevation gradient, site type, and for the following tree species: *Picea abies*, *Pinus sylvestris*, *Abies alba*, *Fagus sylvatica*, and *Quercus* sp. Our results show that these species can be divided into three groups: (i) species with a clear elevation productivity optimum (*Picea abies*, *Abies alba* - unimodal response to elevation gradient), (ii) species with pronounced negative slope in stem basal area from low to high elevation (*Fagus sylvatica*, partly *Quercus*), (iii) species with ambiguous elevation trends in stem basal area (*Pinus sylvestris*, partly *Quercus* sp.). All species exhibited a consistent increase in stem basal area between 1990 and 2015 homogenous along the elevation gradient. The only

exception was *Picea abies* with a reduction in stem basal area increase towards the highest elevations. This seems to be counter-intuitive, however, it reflects the deep growth depression between the 1970s-1990s which had not been compensated by growth increase after the 1990s. Among two species with pronounced optimum in stem basal area at elevation gradient (*Picea abies* and *Abies alba*), only *Picea abies* showed a slight upward shift of peak in stem basal area, approximately by 80 m. Our results identify species such as *Fagus sylvatica* maintaining high productivity also in warm lowlands. We also highlight that recent growth increases have not been sufficient for high-elevation *Picea abies* to compensate for past growth depression, and as a result, the 2015 stem basal area remained similar to 1990.

Intra-specific variation in the climate sensitivity of tree growth - comparing European beech provenances along an environmental gradient

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It is well recognised that climate warming occurs worldwide, inducing longer and more intense drought periods. Considering that this trend is predicted to further increase, exploring the responses of trees to climate variability and extreme events is of crucial importance. At European level, several climate change-induced forest dieback events have already been observed, posing questions on how to manage forests in the future, in particular which species and (or) provenances to promote. For the latter, provenance trials offer a suitable tool as they allow to compare the intra-specific local adaptation potential of trees originating from different locations. In this study, we explored relationships between tree-ring width and climate for European beech (*Fagus sylvatica* L.), a tree species of major economic and ecological importance in Europe. More specifically, we analysed the climate sensitivity and resilience to extreme events of 24 provenances growing at three sites along an environmental gradient in Germany. Preliminary results show that beech is generally limited by water availability, but that this sensitivity as well as the resistance/resilience to extremes differs between provenances and sites. The existence of intra-specific variation in climatic responses of beech may be used to inform forest managers on which provenances to choose in reforestation.

Intraspecific variations in the radial growth response to drought of *Pinus halepensis*

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Extreme drought episodes have been reported to cause significant losses in forest productivity, and lead to dieback events for many tree species in several biomes. Although drought impacts on tree secondary growth have been largely studied at various temporal and spatial scales, how growth resilience to drought varies across a species distribution range remains unclear.

We focused on Aleppo pine (*Pinus halepensis* Mill.) as it is the main conifer species of the western Mediterranean basin and considered as one of the most drought-tolerant tree species in Europe. To assess the variability in growth response to drought across the species distribution range, we gathered a large tree-ring dataset of 4632 pre-existing tree-ring width series from 281 sites located in 11 countries across the Mediterranean basin. Since such dataset does not provide an understanding of the origin of the observed variability (genetic adaptation to local conditions and/or phenotypic plasticity), we supplemented this analysis with the study of a common-garden experiment established in 1976 in southeast France. There, tree ring-widths were measured from 195 individuals of 12 *P. halepensis* provenances originating from six countries. For each year and each site (including the common garden), we quantified resilience in terms of radial growth and its components, resistance and recovery, respectively accounting for the impact of the perturbation and the capacity of the tree to recover from it. Relative drought intensity was assessed using SPEI (Standardized Precipitation Evapotranspiration Index), a climatic standardized water balance index.

Based on the large ring-width database, we found that (a) resilience was more affected by the water balance before and after the drought than by the intensity of the drought itself; (b) there were strong variations of growth response to drought among *P. halepensis* populations, with trees growing under drier climates being more sensitive to drought: they showed a lower resistance, but higher recovery. (c) In contrast, at the common garden, all populations had a similar growth response to drought regardless of their climate of origin.

These results highlight the strong variability in growth response to drought along the species distribution range. Unexpectedly, drought intensity had only a limited effect on resilience, outlining *P. halepensis* great capacity to cope with water scarcity. Our results at the common garden suggest that this could be mostly linked to the species high phenotypic plasticity, questioning the relevance of assisted migration strategies in order to reduce forest vulnerability to drought for this species. However, those results need to be confronted to the study of other common gardens located under harsher climatic conditions, where some intra-specific differences in resilience to drought might be revealed.

A multi-indicator approach of drought impacts on *Pinus halepensis* growth in a long-term rainfall exclusion experiment

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The impact of drought on the radial growth of Mediterranean trees has been widely studied. However, little is known regarding its effect on the annual development of branches, leaves and reproductive organs, while these traits are key drivers of tree functioning such as its carbon and water economy, and could provide more promising indicators of climate change compared to the commonly used radial growth indices.

To quantify the impact of drought on these different growth traits, we monitored Aleppo pine (*Pinus halepensis*) annual growth from 2008 to 2022 on 11 trees at the ICOS experimental site of FontBlanche, South-Eastern France. Four of these trees were included in a rainfall experiment where 30% of the natural rain are excluded by PVC gutters, thus simulating a sustained increase in drought intensity. We measured annual diameter growth, shoot and leaf elongation, as well as the number of yearly growth units (as Aleppo pine is prone to polycyclism), ramifications, and reproductive organs on ~30 branches per tree. The measured branches differed in their architectural order, expositions and vertical positions within the canopy.

The quantitative analysis of the variations in these growth variables among years and between the rainfall exclusion and the control plots reveals that needle length and the shoot length of third-order branches were the most drought-sensitive traits. In contrast, the impact of drought on secondary growth was much less significant, while second-order shoot length, polycyclism and the number of reproductive organs did not show a consistent response to drought.

Needle and third-order shoot lengths thus seem to be the most responsive and reliable indicators of drought stress, revealing that Aleppo pine primarily adjusts its primary growth to reduce water demand. Our results also highlight the strong interest of simultaneously monitoring the development of the different tree compartments, allowing the use of a comprehensive multi-indicator approach to better quantify the impacts of drought on tree growth.

“Tree ring” chronologies in perennial herbs from semi-natural grasslands in Latvia.

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Semi-natural grassland is a very species-rich ecosystem that requires management to maintain it. In Latvia only 0,1% of its territory consists of biologically valuable natural grasslands and are considered endangered. Determination of plant establishment and age structure help discover plant population dynamics, climate impact and gain the necessary information to prescribe new or improve existing grassland management systems. Perennial herbs could also be possible indicators of grassland longevity but thus far there has not been an easy and efficient method to gain access to their chronologies. In this research as the study area for semi-natural grasslands Krastiņi in the protected landscape area “Ziemeļgauja” was chosen in which the samples of biologically valuable grassland indicator species - *Filipendula vulgaris* - and *Achillea millefolium* were taken from five grassland plots that were last plowed at different ages. The main goal was to create chronologies for both species and determine age differences of the two species between the different aged grassland plots and whether they could be used as indicators of longevity. The age was ascertained by making a cross section of the rhizome, annual rings were counted and measured.

Dry and hot years drive growth decline of *Pinus halepensis* at its southern range limit in the Moroccan High Atlas Mountains

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Climate change is increasing the frequency and intensity of extreme droughts in the northern hemisphere, leading to forest decline and tree mortality. Species are more vulnerable to climate fluctuations at the rear edge limits of their distribution ranges. *Pinus halepensis* is a Mediterranean conifer with its southern distribution limit in the High Atlas Mountains of Morocco. The purpose of this study was to analyse the climate-response of *P. halepensis* tree-rings from the High Atlas Mountains of Morocco, and to determine its resilience to extreme drought events. Climate data for the study site revealed that temperature has significantly increased in recent decades, but precipitation remained unchanged, resulting in increased aridity. The ring-width time-series revealed several missing rings since 1999, possibly linked to the increased aridity. Tree-ring width responded negatively to spring and summer maximum temperature and positively to previous winter and spring precipitation. Moving correlation analysis revealed an increased negative relation with maximum temperature in April, June, and July, supporting the adverse effect of global warming on *P. halepensis* growth. Resilience analysis revealed that trees were able to recover from extreme droughts, but its detrimental effect remained in the following years. *Pinus halepensis* trees in its southern distribution limit are already suppressing growth in extreme drought years. If the frequency of extreme droughts increases, as predicted by climate change models, the recovery capacity of these trees will be compromised, resulting in habitat loss and in the contraction of the species southern range.

Exploring the climatic and non-climatic fingerprints of the hydrogen isotope signals in tree rings

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The analysis of a Europe-wide network of tree-ring stable isotopes has shown that the climatic signal of $\delta^2\text{H}$ in tree-ring cellulose ($\text{C}_6\text{H}_{10}\text{O}_5$), is far weaker compared to those recorded in carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotopes. Furthermore, the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ relationships were shown to be site dependent and significantly deviated from the Global Meteoric Water Line. These results suggest that non-climatic effects are modifying the hydrological signature of $\delta^2\text{H}$. Recent experiments have underlined the potential of $\delta^2\text{H}$ in tree-ring cellulose as a physiological indicator of shifts in autotrophic versus heterotrophic processes. However, the impact of these processes has not yet been quantified under natural conditions.

Defoliating insect outbreaks can disrupt photosynthetic production and carbon allocation, stimulating the remobilization of stored carbohydrates. Such disturbance events therefore provide unique opportunities to evaluate the impact of changes in the use of fresh versus stored non-structural carbohydrates, i.e., of non-climatic signals stored in $\delta^2\text{H}$. By exploring a 700-year tree-ring record from Switzerland, we assess the impact of 79 larch budmoth (LBM, *Zeiraphera griseana*) outbreaks on the growth of its *Larix decidua* host trees.

LBM outbreaks significantly altered the tree-ring isotopic signature, creating a ^2H -enrichment and a depletion in ^{18}O ^{13}C . Changes in tree physiology during outbreak years are shown by the decoupling of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ (O–H relationship), in contrast to the positive correlation in non-outbreak years. The O–H relationship in outbreak years was not significantly affected by temperature, indicating that non-climatic physiological processes dominate over climate in determining $\delta^2\text{H}$ variations. We conclude that the combination of these isotopic parameters may serve as a metric for assessing changes in physiological mechanisms over time

and that hydrogen isotopes can be considered as a proxy for non-climatic disturbance signals in dendrochronological research.

Divergence in leaf and stem phenology between ring-porous and diffuse-porous species and the impact of phenology on tree growth

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Plants leaf and stem phenology plays a critical role in species performance and distributions and mediates the impacts of biotic and abiotic conditions on plants growth. Despite the importance of phenology, we have limited understandings of differences in phenology among species based on physiological mechanism and have seldom researches on phenological constraints on plant growth. Most of previous studies on plant phenology, especially the stem phenology, only focused on gymnosperms and few species. In our study, we selected 10 dominant angiosperms tree species in typical temperate forest, five diffuse-porous species and five ring-porous species, to test how leaf and stem phenology differs between ring- and diffuse-porous species and how phenology impacts on tree growth. Our results found that ring-porous species unfolded leaves later but produced vessels earlier compared with diffuse-porous species, while ring- and diffuse-porous species have non-significant differences in cessation of xylem growth as well as leaf fall. Considering about the xylem formation progress, ring-porous species have two peaks of stem growth while diffuse-porous species only have one, which is consistent with the differentiation of xylem into early wood and late wood in ring-porous species. We also found that stem phenology have close association with stem growth. The later cessation of xylem cells growth the wider stem growth width they had. The earlier beginning of xylem cells growth, the wider stem growth width they had in diffuse-porous species while in ring-porous species, they have the opposite trends. Ring-porous species show lower growth sensitivity to temperature than diffuse-porous species based on the difference in stem phenology between them. Our study not only systematically demonstrated the differences in leaf and stem phenology, especially the wood formation process, between ring- and diffuse-porous species, but also explained the difference in growth sensitivity between ring- and diffuse-porous species in response to environmental conditions from the perspective of wood formation processes. Our results also have certain implications for the researches of differences in the response of tree growth to climate change among different wood types.

Effects of the Itoitz dam (Navarre) on the growth of the dominant riparian tree species

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Introduction: Floodplain forests are very dynamic ecosystems due to the hydrologic regime variability (e.g. water level, timing, frequency). The dominant trees of these forests are highly dependant on the specific flood regime causing these variations. However, hydrological alterations such as regulation caused by dams affect directly the water regime, which may have an impact in the diversity of the floodplain forests and the growth of the dominant trees.

Study area: Itoitz dam was built in 1998 on the main course of the Irati river (Navarre, Spain), located in the transition between the temperate and the mediterranean climates. Before dam construction, riparian vegetation was mapped, and plant communities were sampled by means of vegetation plots all along main river and its tributaries.

Aim: The aim of this study is to assess the effect of the dam on the growth of the dominant trees of the riparian forests naturally occurring in the target rivers.

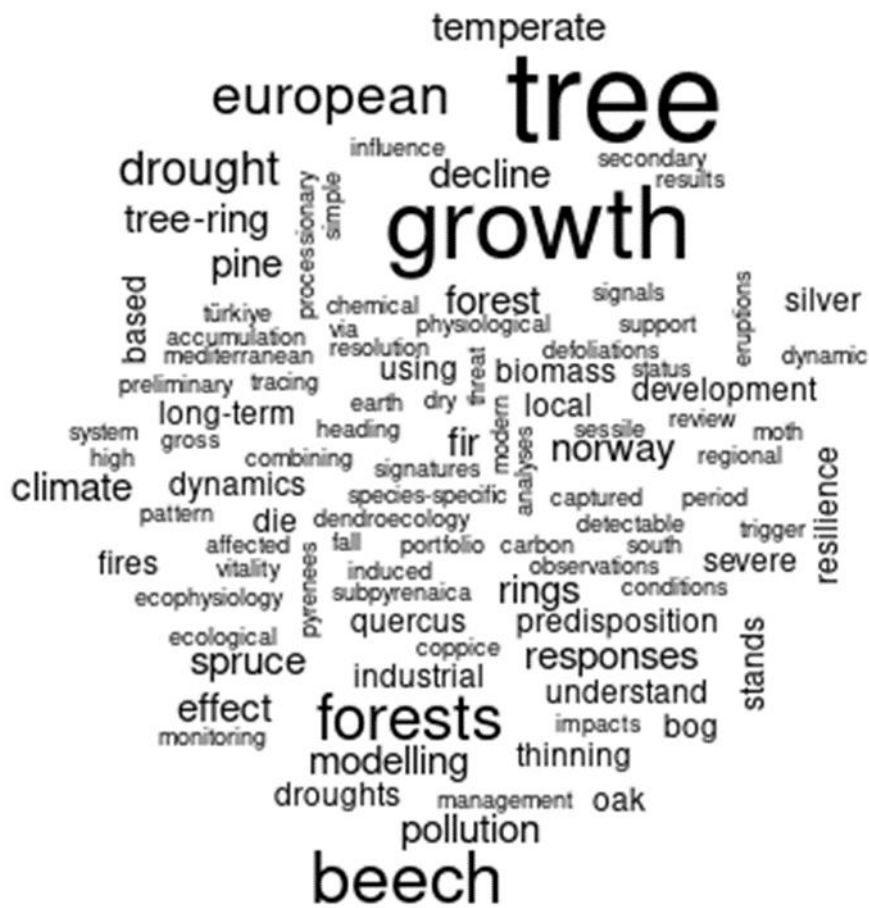
Methods: The selected study species were *Alnus glutinosa* (Ag), *Fraxinus excelsior* (Fe) and *Fraxinus angustifolia* (Fa), which are the most frequent tree species within the riparian forest, linked to fluvial dynamics. The sampling strategy considered river sections affected by the dam and those not affected. Additionally, several tributaries were sampled as a control. In total, 24 localities were selected evenly distributed in the mentioned river sections. At each sampling point 10 individuals of each species were sampled, extracting two cores from each tree. A total of 240 trees (80 Fa, 80 Fe and 80 Ag) were sampled by dendrochronological methods during the autumn of 2022. When selecting the trees, an attempt was made to ensure that they had some special characteristics: a minimum age of 40 years (25 cm for ash and 30-35 cm for alder), proximity to the riverbed and the minimum possible height from the river. Once the trees were selected, different measures were obtained in the field for each tree (distance to the river, tree height, soil type, DBH, number of trunks and their condition, inclination of the tree, ...). At the laboratory, the samples were glued on wood strips and processed for further analysis. The dating and measurement were done with a LINTAB measurement table. The data obtained was converted using the software TRICYCLE to later use the COFECHA program to ensure the quality of the dating and measurement. The impact of the dam in tree growth was assessed by changes in the basal area increment (BAI) index.

Results: *Alnus glutinosa* occurs in the upstream and downstream sections of the dam, but not in the forests of the control rivers. Ashes occur in all the studied river sections, but upstream of the dam (i.e. North, temperate) the ash species is *Fraxinus excelsior*, and downstream (i.e. South, Mediterranean) *Fraxinus angustifolia*. Preliminary growth analysis shows that, in comparison to alder, both ash species showed less mean annual ring width, being much older in relation to their size than alders. Regarding the growth patterns, both ash species presented better population chronologies while alder seem to show a more diverse individual response among sample trees in the same site. These results suggest the existence of species-specific growth patterns as a response to hydrological changes.

Forest Health Session

Moderator

Daniele Castagneri, Università degli Studi di Padova, Italy



A more physiological dendrochronology to improve Earth system modelling using tree rings

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Forests capture almost a third of global anthropogenic carbon emissions to the atmosphere each year, slowing down the pace of climate change. However, current projections of the capacity of forests to remain as a carbon sink through the century are highly uncertain. This uncertainty is about four times larger than in the ocean carbon sink due to difficulties to constrain climate-vegetation feedbacks in the Land Surface Model (LSM) component of Earth system models (ESMs). LSMs have been developed, parameterized and benchmarked using short-term observations. Their projections diverge towards longer time scales, mainly because of missing processes and the lack of long observational constraints. Tree-ring data provide a long-term observational record of forest growth and water-use efficiency that has recently emerged as a novel benchmark for next-generation LSMs, such as the ORCHIDEE LSM - the terrestrial component of the French IPSL ESM. Yet, this emerging research demands concerted advances in the observations and in modelling to integrate and constrain the representation of carbon source (photosynthesis) and carbon sink (wood formation) processes of biomass growth activity in LSMs. This talk will present conceptual advances towards “physiological dendrochronology” and outline a new tree-ring data-model framework to reach the goal of constraining projections of the terrestrial carbon cycle in LSMs. The data-model framework will be developed as part of the EU-funded CATES ERC starting grant over the next 5 years and should foster a close collaboration between the tree-ring and Earth system modelling communities. This is expected to stimulate the development of a network of paired tree-ring (ring width, isotopes, xylogenesis, dendrometers) and ecosystem (eddy covariance, micrometeorology) observations of source-sink growth activity and inspire a new generation of modellers in the tree-ring community.

Mercury in tree rings of five species

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Using trees as an archive of environmental pollution could be very useful for regions where pollution monitoring has not, or only recently, been implemented and no geochemical archives are available. Mercury (Hg) is a promising trace metal for the reconstruction of historical air pollution, since its primary uptake pathway has been found to be from the air by the leaves, from where it is transported through the phloem to the tree rings. Tree-ring concentrations of other pollutants, on the other hand, may be more influenced by their concentrations in the soil. Although several authors have found that tree-ring Hg concentrations reflect atmospheric exposure concentrations, this was not the case for all studies on this topic. One of the reasons for the lack of consensus is that the abiotic and biotic factors that influence the Hg concentration in tree rings are not yet well understood. The aim of this study is to 1) identify some of the factors that influence the Hg concentration in tree rings and 2) verify if these factors differ between tree species.

Our study area is Ústí nad Labem in the Czech Republic, a contaminated environment for which extensive historical air pollution data are available at the Czech Hydrometeorological Institute. Five tree species (*Larix decidua*, *Abies alba*, *Robinia pseudoacacia*, *Acer platanoides* and *Prunus avium/cerasus*) were sampled with an increment borer. Per species, cores from 5 trees were obtained. The tree rings were measured and dated using standard dendrochronological methods. Next, the cores were cut into separate annual rings and freeze-dried. Hg in each ring was measured with cold vapour atomic absorption (CV-AAS) in an AMA 254 Hg analyser. Principal component analysis and linear mixed models were used to identify the variables that correlate best with the Hg concentration in tree rings. The variables included were historical atmospheric Hg⁰ concentration, tree-ring width, climatological conditions, tree-ring water content and whether the ring is part of the sapwood or heartwood.

The Hg concentration in tree rings shows a high variability between species and within species (between individual trees). Furthermore, the variables that correlate with Hg in tree rings differ between species. In larch, raw tree-ring width was found to be the factor with the highest correlation with Hg concentration in the rings. An explanation could be that higher stomatal conductance in years with good growth conditions (especially enough summer precipitation) results in photosynthesis products with more Hg bound to them. In species other than larch, tree-ring water content was the factor that showed a significant correlation with

tree-ring Hg. The atmospheric Hg concentration generally did not have a significant correlation with Hg in tree rings, and when it had, it explained little variance.

The results suggest that Hg in tree rings is influenced by several factors other than Hg in air, and that some of these factors have a larger effect. Additionally, they vary between tree species. Further research is needed to better understand the processes that influence Hg concentration in tree rings, so that they can be considered in models for reconstructing past atmospheric Hg concentrations.

Tracing volcanic eruptions and anthropogenic pollution in tree rings: preliminary results from Hg and synchrotron-light chemical analyses

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We analysed larch trees from high elevation in northern Italy for Hg with a Lumex RA-915M Mercury Analyzer with pyrolyzer PYRO-915+) and for S, Zn, Cu, Ni, Pb (by synchrotron light X-ray fluorescence at beamline i18 Diamond Light Source, UK). Hg analyses were performed on 11 single rings per sample centred on the year of a known volcanic eruption. The in-situ synchrotron analyses were carried out on longer timeseries of up to 150 years with a maximum replication of 5 samples. We detected significant peaks of volatile elements in tree rings matching periods of repeated volcanic eruptions with high volcanic explosivity indices (VEI 5-6, out of a maximum of 8). A good example is shown by increased Zr, Cu, S, Pb occurring during the decade 1875-1886 corresponding to eruptions of the volcanoes Askja (Iceland, year 1875, VEI 5), Vesuvius (Italy, 1875), Cotopaxi (Ecuador, 1877, VEI 4), Krakatoa (Indonesia, 1883 and 1884, VEI 6) and Okataina (New Zealand, 1886, VEI 5). Furthermore, during the last 3 decades of the XX century, we observed a monotonic long-term increase of the elements Pb, Ni, Zn and Cu in association with a significant reduction of the tree-ring widths. We consider the chemical shifts and the abrupt growth reduction as reflecting anthropogenic pollution mainly related to a sustained and increasing use of fossil fuel, in particular leaded gasoline. Notably, the chemical contamination in the analysed wood decreases significantly in the first decade of the XXI century, when unleaded gasoline was substituted the Pb-rich fuels. Both these approaches seems promising in detecting hidden effects of volcanic or pollution activities when other tree-ring traits do not show any other peculiar feature.

Variable influence of competition on tree growth response to drought. There are no simple recipes for forest management

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The analysis of the resilience components, namely resistance, recovery and resilience, has found wide application in tree-ring science since the seminal paper by *Lloret et al.* in 2011. Among others, many studies have investigated the effect of competition on tree growth response to climate extreme events using the three resilience indices. These studies can have important repercussions for forest management. Indeed, competition can be modified by silviculture, specifically thinning can reduce the intensity of competition.

We here present the results of a meta-analysis on the resilience components used to investigate the effects of competition on tree growth response to drought. Of the 166 cases reviewed, 79 provided quantitative information and were used to fit random-effects model to estimate the mean effect size of competition on the resilience components.

We observed that competition had a negative mean effect on resistance ($p < 0.001$), i.e. rings during drought events were narrower in denser stands. However, large variability was observed among different cases. Moderators that describe site, stand, or species characteristics were not able to further explain this variability. The mean effect of competition on resilience was not significant ($p = 0.40$). Finally, the mean effect size of competition on recovery was positive ($p = 0.04$), but this was probably linked to the inverse relationship of this component with resistance.

Our study indicates that competition influence on growth response to drought is quite variable. In general, reducing competition can improve resistance, while no general conclusion can be driven on the capacity of trees to return to pre-drought growth rates, i.e. resilience. Large variability of results from different cases, and the scarce capacity of moderators to explain such variability, suggest that specific conditions modulate different effects of competition on growth responses. Therefore, reducing competition between trees through thinning cannot be considered the universal solution to improve tree capacity to be resistant, and especially resilient, to drought.

Effects of industrial activity and air pollution on beech trees in Transylvania, Romania

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The development of urban areas, industrialisation and increasing road traffic intensity is a global problem of air, soil and water pollution, with negative effects on forest ecosystems and wildlife. Trees play an important role in pollution control by filtering the air and reducing the negative effects of pollution. The use of plants and trees as bioindicators of air pollution has for many years been a simple and effective way of highlighting the effects of pollution on forest ecosystems. This study provides a detailed analysis of the negative effects of air pollution on beech trees (*Fagus sylvatica* L.) in the region of Copșa Mică, Romania. In this region, industrial activity such as non-ferrous metal processing and carbon black manufacturing started in 1936 and developed continuously until 1990. After 1990, the industrial activity was significantly reduced and stopped in 1993. Three areas with different degrees of damage were investigated: intensively polluted area, moderately polluted area and unpolluted area. By analysing the beech trees increment series, growth losses were highlighted during the period with intensive industrial activity, especially in the intensively polluted area. Resilience indices showed the period when intensively affected trees were able to recover growth lost during the period of very high industrial activity. Regarding the dendroclimatic response of trees, it is shown that monthly rainfall in the April-August period positively influenced tree growth, while monthly mean temperatures in the April-September period are negatively correlated with tree growth. The dendroclimatic models differed according to pollution intensity. Correlations with climate variables over different periods revealed a change in the response of trees affected by local pollution to the climate, compared to unaffected trees at times when air pollution was very high. Chemical analysis of tree rings over a period of 60 years showed that trees are able to accumulate heavy metals. Five heavy metals (Cu, Zn, Mn, Fe and Ni) were identified in the composition of the tree rings, the concentrations of which showed statistically significant differences at a 95% confidence interval in relation to the level of pollution.

Drought resilience and ecological value of coexisting planted silver fir, Norway spruce and Douglas fir trees

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Forests worldwide are threatened by increasingly frequent and severe droughts and heatwaves by undergoing worrisome decline and mortality events. Under these circumstances, there is a whole debate on what should be done in order to have climate change adapted forests, i.e., healthy ecosystems that provide key ecosystem services, including climate change mitigation, and concurrently satisfy the needs of the human society in a sustainable way. What tree species to plant, maintain or favor in detriment of others and where, are fundamental questions that need to be taken into account in this regard. Planting non-native, fast-growing and drought-resistant tree species has been many times suggested as a solution. Nevertheless, their drought resistance is commonly assessed in their natural habitats thus neglecting that their response to drought may vary considerably when planted outside their natural distribution range. Here, we study three mixed plantations of silver fir (native to Romania), Norway spruce (largely planted all over Europe) and Douglas fir (non-native to Europe), located in the SW of Romania. Our aim is to deepen into the drought resilience and ecological value of these three conifer species and see how they respond to climate when growing under the same environmental conditions. For this, we are using tree rings along with competition and diversity indices, which will help us understand the resilience and stability on the long-run of these conifers to challenging climate change conditions. Our preliminary results show that the silver fir trees have positive growth tendencies no matter the study site. However, in the case of the Norway spruce and Douglas fir trees, it seems that the growth tendencies are very variable among the three mixed plantations and depend more on the (micro)climatic conditions of each study site. As regarding the Hegyi competition index, no significant differences have been found between the three species within each study site although this index did differ significantly between the three mixed plantations. In situ quantifications of how coexisting native and non-native planted conifers perform are scarce but highly valuable. These preliminary results support the idea that there is no easy and unique way to answer fundamental questions such as "What tree species to plant, maintain or favor in detriment of others and where?"

A multi-proxy tree-ring approach to identify pine processionary moth defoliations

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The Pine Processionary Moth (*Thaumetopoea pityocampa*; PPM) is the main defoliating insect of Mediterranean pines and cedars. PPM larvae feed on needles during the winter, eventually reaching intense defoliations and driving conspicuous growth reductions. Under warmer winters the frequency and intensity of PPM defoliation events are expected to increase. Despite this potential threat, we currently lack tools to reconstruct and contextualize PPM attacks across time and space at the tree level, and thus to determine their impacts on tree carbon and water economy. The aims of this study were (1) to identify changes in tree-ring traits as proxies of PPM incidence; and (2) to understand the influence of PPM defoliations on water and carbon acquisition and use in different pine species.

We sampled six forests in Spain comprising four pine species: *Pinus nigra* (3), *P. halepensis* (1), *P. pinaster* (1) and *P. sylvestris* (1). According to the Regional Forest Services data, all forests have experienced PPM defoliations in the last decades. We sampled thirty trees per stand along a gradient from edge to center. We collected four cores per tree, two for tree-ring width chronologies, and the other two for carbon isotope and microdensity analyses. First, we identified potential years associated with a PPM event, i.e. tree rings with sudden and conspicuous growth reductions not present in all trees. Second, we validated PPM incidence in these years by comparing Landsat data at the stand level between the spring of potential years and the autumn of the precedent year. In addition, we carried out an analysis of interannual variations of the Normalized Difference Vegetation Index (NDVI) values to detect anomalies in the primary productivity. Once the PPM incidence was validated, we carried out a multi-proxy characterization of these tree rings. We fitted linear mixed-effects models (LMMs) of Basal Area Increment (BAI) using a multiscale drought index as predictor to distinguish the growth reductions attributable to climate (e.g., droughts) from those due to PPM outbreaks. Finally, we quantified carbon isotope composition to calculate intrinsic water use efficiency, and microdensity variables using tree rings.

Our results indicate a BAI suppression the defoliation year higher than 70% in the case of *Pinus nigra*, and ca. 50%, 35% and 25% in *Pinus pinaster*, *Pinus sylvestris* and *Pinus halepensis* stands, respectively. Remote sensing analyses support the dendrochronological results, as we observed a decrease of primary productivity through NDVI between the defoliation year and the prior autumn. LMMs showed negative residuals of the climate-modelled BAI values during years with predicted PPM defoliations. Concerning the isotopic rates and microdensity analyses, we hypothesize that severe defoliation years are characterized by a reduction of the maximum density, with thinner cell walls, and lower C¹³ concentrations because of reduced water stress due to canopy loss. This multi-proxy approach enables the detection of PPM defoliations, providing a tool to monitor PPM incidence and dynamics in the current global change context.

Modelling secondary tree growth of European forests based on high resolution satellite observations and climate data

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Under climate change, modelling forest productivity is gaining increasing attention since forests on the one hand contribute to climate change mitigation by carbon sequestration and provide wood as an important renewable resource, and on the other hand increasingly suffer from extreme events such as droughts, late-frosts, and other disturbances. Despite major advancements in tree-growth modelling over the past decade, we still lack observation-based (in contrast to simulated) high-resolution, gridded forest growth products that could help to provide a better mechanistic understanding of forest responses to climate change, potentially improving mechanistic model parameterization.

Within this context, tree-ring measurements render an invaluable source of information since they approximate annual above-ground tree growth – and thus net primary production (NPP) – fairly well. Yet, tree-ring records represent local tree growth, which implies the necessity to

upscale these NPP-proxies to stand and landscape levels to achieve gridded products. A well-known means to model tree growth is using climate data, since tree growth to a large degree is governed by environmental conditions. However, local site-conditions modulate how climate translates into growth, therefore site-specific information is required to improve models based on gridded climate data. Here, earth observation from satellites (EOS) may render a valuable and relatively easy-to-obtain source of additional, site-specific information. This is because canopy reflectance in different bands (e.g. near infrared, red-edge, red) is closely related to the photosynthetic activity and thus NPP. Consequently, deploying gridded, open-access EOS data for improving growth predictions into space appears to be a promising research avenue. To date, the existing studies combining tree-ring data with EOS are mostly constrained to high latitudes (due to a very distinct growing season) and typically deployed EOS featuring coarse to moderate resolution. Consequently, assessing the potential of high-resolution (10 m – 20 m) remote-sensing missions such as Sentinel-1 and Sentinel-2 in mid-latitude forests will provide novel insights into modelling secondary tree growth.

Within this framework, we recently assembled the TREOS-network. TREOS represents a sub-continental tree-ring network for eight common tree species in Central and Eastern Europe comprising 697 sites and spanning the region between 41.0 and 59.6° latitude and 5.6 and 27.9° longitude. For all sites, we extracted Sentinel-1 and Sentinel-2 time series of various bands along with gridded climate products and used various combinations of these explanatory variables to model tree growth as approximated by stand-level tree-ring chronologies. Species-specific models explained up to 70% of tree-growth variance, whereas clade-specific (i.e. gymnosperms vs. angiosperms) models performed worse (up to 30%), indicating the necessity to account for species-specific relationships. When implementing EOS data within multiple regressions model performance improved by up to 45%. In conclusion, these results indicate EOS- and climate-based gridded growth simulations to be generally feasible. Yet, problems related to species-specificity have to be solved, e.g. by deploying EOS-based tree-species classifications as a required source of information when projecting our models into space.

Using modern day bog pines to understand ancient bog pine growth and decline

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Scots pine (*Pinus sylvestris*) woodland was extensive across Scotland in the early Holocene, reaching a maximum extent ~7-8000 years ago, before experiencing a widespread contraction. The timing and dynamics of this 'pine decline' appears to have varied spatially and temporally, and the causal drivers are not well understood. Extensive sampling of peat-preserved sub-fossil material from a high elevation (~550m asl) site (Einich) in the Cairngorms, has identified material dated to ~7800 years BP. An initial cross-dated floating chronology (n = 20 trees) encompasses the period 7866–7507 years BP. This chronology represents the first colonisation phase of Scots pine into these high elevations in the early Holocene period. Other dated samples suggest that this particular pine woodland existed until ~6500 years BP, and continued measurement and cross-dating of sub-fossil material aims to create a continuous millennial chronology from which we hope to explore the “decline” phase of this woodland.

To elucidate potential primary climatic drivers of these early-mid Holocene pine woodlands, we have sampled a range of modern-day bog pine sites, and co-located mineral soil sites, to explore modern-day relationships between tree growth parameters (ring-width (RW) and Blue Intensity (BI)) and climate. These living bog pine sites, some of which may represent modern day analogues of the Einich site, represent a transition of hydrological stress, including one representing a bog woodland in decline (with ~50% dead trees, and many trees showing a pronounced suppression from the 1950s). Summary statistics (e.g., mean growth rate, mean sensitivity and 1st order autocorrelation) were compared between the sub-fossil Einich chronology; the living bog pine sites; and mineral soil pine sites in the region; to distinguish which of the modern sites the sub-fossil samples most closely represent. Sliding correlation analysis and response function analysis were used to explore the climatic signal expressed in the different living site tree-ring parameters, and the temporal stability of the relationships.

Mean RW (0.45mm) is lowest at the extreme hydrologically-stressed declining bog pine site ('RMB'), and this site further has the greatest mean sensitivity (0.3). In these two properties, the characteristics of the Einich sub-fossil material are most similar to the declining RMB site. The RMB site, when compared to the other bog pine sites using sliding Spearman correlations, shows a decreasing between-chronology coherence since the 1950s, and maximal suppression (with unmeasurable rings and substantial tree mortality) from the late 1970s. RW

expresses no climate response, but latewood BI and delta BI show some positive summer temperature response – though the response is weaker for bog sites than mineral soil sites. The strongest coherent response for all bog and mineral soil sites is between earlywood BI and February–March temperatures. However, this signal also weakens in the recent period for the RMB site.

Understanding the drivers of bog pine trees is complex as local bog hydrology likely dominates growth rates and modulates the wider response to climate. The RMB living site however does appear to express similar properties to the sub-fossil Einich site, and likely will provide a useful modern analogue for more refined modelling of the controls on bog pine growth, and drivers of decline.

Thinning induced changes in *Quercus robur* radial growth in mixed stands

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With aim to increase survival and promote regeneration of pedunculate oak in the transition zone of boreal and nemoral forests, selective thinning i.e. removal of other tree species and shrubs in the vicinity of the oaks, is practiced. This forest management method improves the light conditions for the selected remaining trees and other species associated with them, but can have a contrasting effect on the growth due to the changed microclimate. In this study the response of radial growth of oaks to drastic environmental changes caused by selective thinning in mixed stands is analyzed.

Increment core samples were collected from two oak stands where thinning had been carried out, tree ring measurements and cross-dating was performed. The similarity of the growth of oak trees in both stands was assessed by Principal components analysis (PCA). To determine whether thinning had changed the trends in oak growth sensitivity to meteorological factors the chronological cluster analysis was used. Modelling of the relative cumulative radial increment of oaks was performed.

Thinning did not cause changes in oak growth sensitivity. Removal of spruce in mixed stands improved radial growth for approximately half of studied oaks, while the rest had negative or no changes in radial growth. Thinning year, oak cambial age and local stand factors had individual rather than systematic effect on relative cumulative radial increment of the oaks after thinning.

In light of estimated uncertainty, the ongoing research will be devoted to determining the interaction of stand composition and thinning intensity on the further growth of oaks, as well as the association between intense thinning and mortality of oaks. The study is being conducted under the framework of a/s “Latvijas Valsts meži” project “Effect of climate change on forestry and associated risks”.

Joint effect of severe heatwaves and droughts likely contributes to a rapid growth decline of silver fir in Central European temperate forests

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Prolonging drought periods and more severe heatwaves pose a significant threat to the stability of forest ecosystems. Silver fir is currently considered one of the more resistant species suitable for future adaptation and mitigation strategies. However, the potential is not well understood for the central parts of Europe. Here we present a dendroecological study of the joint effects of droughts and heatwaves on the growth of silver fir. We used tree-ring width series of 96 dominant individuals collected during the period of 2016 – 2019 in the region of Western Carpathians on the elevational gradient ranging from 200 – 1480 m a.s.l. Long-term growth trends suggested a recent rapid growth decline compared to the beginning of the 21st century on the whole elevational gradient. Although no change of trend in the frequency and intensity of droughts during the vegetation period was observed, the frequency, intensity and temporal resolution of heatwaves were rising not only in lower areas of distribution but on the upper edge of the current species distribution as well. Furthermore, there was a more frequent combination of severe heatwaves and droughts after 2000. Here, we found statistically significant growth reduction during years with the joint effect of severe droughts and severe heatwaves in the lower parts of the elevational gradient and severe droughts without heatwaves in the middle and upper parts. This finding reveals heatwaves as an important ecological factor that should be considered in future dendroecological studies.

Combining dendroecology in old-growth forests and dynamic vegetation modelling to infer development and long-term dynamics of beech-fir forests in the Pyrenees.

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Old-growth forests are an invaluable source of ecological information on long-term forest dynamics and development. The extent of temperate old-growth forests in Europe has decreased over the centuries because of forest management, and most forests show evidences of human activities. Some forests where management stopped centuries ago are slowly recovering many old-growth attributes but are still affected by management legacies. Disentangling the different effects of past human disturbances and climate on current species composition is crucial for understanding the long-term development of forests under global change.

Here, we investigated disturbance and recruitment dynamics in two forests in the Western Pyrenees (Spain) dominated by the two shade-tolerant species *Fagus sylvatica* (European beech) and *Abies alba* (silver fir), but with contrasting management history: an old-growth forest and a long-untouched forest (i.e. not managed or altered by humans over the last hundred years). We set up 3-4 plots in each forest and used dendroecological methods to analyse forest structure, growth patterns and disturbance histories in these forests. To further examine the effects of natural and human-induced disturbances on forest development over time, structure and species composition, we benchmarked field based and dendroecological disturbances and biomass dynamics with a dynamic vegetation model (DVM).

Both study forests differed in their disturbance regimes, but none showed evidence of recent human disturbances or of stand replacing disturbances (either natural or human induced). Over the last four centuries, the dynamics of the old-growth forest was dominated by low disturbance rates and continuous recruitment of beech and fir. In contrast, the long-untouched forest showed evidence of intensive disturbances in 1700-1780, probably by logging. After that, this forest was also dominated by low natural disturbance rates. In both forests, beech and fir recruitment mainly occurred after more intense disturbances, despite the high shade tolerance of both species. DVM simulations closely mirrored potential natural

vegetation of these forests with a dominance of beech over fir, but overestimated the presence of less shade-tolerant species. Some structural attributes in the long-untouched forest converged towards old-growth forest within ~200 years of logging cessation, but legacy effects from those disturbances still affected species composition and structure. In contrast with DVM simulations, silver fir was more abundant in the long-untouched forest than in the old-growth forest, most likely related to its human-induced disturbances in the past. The dominant natural disturbance regimes in beech-fir forests of the Western Pyrenees induce temporal fluctuations between beech and fir abundance, with a natural tendency for beech dominance in advanced developmental stages and low disturbance rates. If past management favoured an increase in fir abundance in the Pyrenees, previously observed local fir decline may result from natural forest successional processes after logging.

Responses of stem and leaf biomass of temperate conifers to drought spells

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Effects of drought spell strongly influence the biomass production of forest ecosystems and may last up to four following years, which affects carbon sequestration. Reactions of forests to drought spells might be influenced by various factors such as topography, size of the tree, and species. Yet the understanding of carbon allocation strategies into trees' above-ground biomass compartments (e.g., stems and leaves) after such drought spells at a landscape level remains limited. We analyzed the responses of *Pinus sylvestris* and *Picea abies* to the four most severe drought years in the time window 1985–2017 in topographically complex landscapes. To represent stem and leaf biomass we used chronologies of tree rings and time series of the Normalized Difference Vegetation Index (NDVI) extracted from Landsat scenes, respectively. We analyzed the responses of tree rings and NDVI to drought spells using superposed epoch analysis and mixed effect models. Our results show that the most severe drought years were 1994, 2003, 2006, and 2015. While the growth of tree rings decreased in two years following the event, NDVI dropped in the drought year and then revealed an increase in the next two years following the spell. In the third year, TRI increased again and in the fourth year, the growth was at the pre-drought level. The growth of stem after a drought spell was significantly influenced by tree size and climatic conditions during the recovery period, while NDVI showed also an effect of topography. Opposite reactions of tree rings and NDVI suggest different allocation strategies up to three years after drought spells.

Tree-ring responses after disturbances in three beech reserves in Bulgaria

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Frequent and various disturbances in European forests in the last decades have drawn the attention of managers and researchers. There are numerous efforts to study the long-term disturbance regimes of different forest types, including beech-dominated. A frequent problem is the lack of continuous monitoring data or historical records. In such cases tree-ring analysis is the source of the most reliable and in some cases the only information. However, despite the advancement of methodological approaches, there is still a need of gathering data on the type of tree responses after various disturbances. We studied forests in three reserves in Central Balkan National Park in Bulgaria. Within them we selected areas, which were disturbed by the combined effect of ice loading and strong wind (2007, Severen Dzendem reserve) and fire (2011, Steneto reserve and 2012, Sokolna reserve). We collected and analyzed tree-ring cores from surviving trees in the formed gaps or on the edges of the fires. Our results point out several types of responses. The trees in the ice-wind disturbance showed both suppressions, including missing rings (38% of the sampled trees) and releases (27%) following the event. In the fire-affected area the trees showed several types of responses. While some had growth releases, others had a sequence of short-term suppression, followed by a release and then by other suppression. This was most likely due to consequent health deterioration due to fungi infections. However, the mortality rate of the fire-scarred beech trees was very high (70%) and most of the surviving trees are expected to die thus limiting the chance to provide tree-ring evidence for such events in future. We conclude that precise dating and studying of the disturbances would be possible only by combined use of data from trees with releases or suppressions and the new cohort occurring after the disturbances.

Norway spruce forest from Eastern Europe under threat? Early warning signals captured in tree rings

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Climate change is affecting forest ecosystems all around the globe, in particular through warming as well as increases in drought frequency and intensity. Possible impacts range from effects on the provisioning of ecosystem services such as carbon sequestration to tree mortality.

Norway spruce (*Picea abies* (L.) H. Karst.) is one of the most important coniferous species at the European level. In the actual context of climate change, especially with the increase in drought severity and frequency Norway spruce is likely to be at risk. Severe droughts during the vegetation period may, for example, negatively affect the resilience of Norway spruce and its' ability to resist bark-beetle attacks. In recent extremely dry years in Central Europe, this has been observed through the large dieback of Norway spruce forests. In Eastern Europe, however, no extensive Norway spruce decline has been reported so far, posing the question how these forests will develop in the future?

To address this question, we present and analyze a tree-ring network consisting of 156 Norway spruce chronologies from Eastern Europe (Romania). As sites were selected along elevational transects in the Carpathians, our network allows to assess future impacts of climate change using a space for time substitution. The focus of our analysis is on the early warning signals of climate-change induced stress: negative trends in basal area increment, increased sensitivity of tree growth, assessed over the statistics first-order autocorrelation and standard deviation and growth synchrony. A clear decrease in basal area increment was observed over the last two decades in the northern part of the Eastern Carpathians, which was more pronounced for younger stands and at lower elevations. At the same time, the first-order autocorrelation showed a sharp decrease at lower elevations. For intermediary elevation in the last two decades, there was observed a decrease in growth synchrony, meanwhile, at higher elevations, growth synchrony increased. Overall, our results highlighted increasing stress conditions of Norway spruce-based forests in Eastern Europe. In the current climatic scenarios, we may expect high mortality and forest diebacks also in the eastern part of Europe. Mitigation solutions are required as soon as possible.

Different climate conditions trigger variations in gross primary productivity and carbon biomass accumulation in two conifer stands in Canada

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The rapid climate change in the northern hemisphere can affect forest carbon sink capacity, playing a crucial role to turn forests into a source or sink of carbon, i.e. allowing for a negative or positive feedback to climate change. The understanding of the long-term seasonal carbon sequestration dynamics and how climate influences this process is still scarce. This research aims to improve our understanding of the impact of long-term climate variability on carbon sequestration and on the link between C uptake and above-ground woody biomass growth, by investigating two conifer stands: *Pinus banksiana* located in a boreal climate (OJP), and *Pinus strobus* located in a temperate climate (TP). Specifically, we used the long-term records of gross primary productivity, GPP, (1999 – 2019 at OJP and 2003 – 2018 at TP) to investigate GPP's inter-annual and intra-annual relationships with xylem biomass accumulation at tracheid scale (i.e cell wall area, CWA) and ring level (i.e ring wall area, RWA) and how these are related to intra-seasonal variability in daily minimum (T_{\min}), mean (T_{mean}), maximum temperature (T_{\max}), precipitation, and vapor pressure deficit (VPD).

We found that CWA and RWA chronologies were strongly and positively correlated with GPP at both sites, but at different times. In OJP, GPP was correlated with CWA during all growing season (April – October), and RWA was correlated one month earlier (March - September). Instead, in TP site, CWA was strongly correlated with GPP during June – August, while RWA, was even strongly correlated with GPP during April – September.

At OJP, GPP was positively correlated with precipitation during all growing season, while at TP GPP was positively and significantly correlated with precipitation during mid spring until early June. Interestingly, GPP correlated strongly and positively with the daily temperature (especially with the T_{\min}) from September until November at both sites. Weak and scattered negative correlations occurred between GPP and T_{\max} during summer at OJP. On the contrary, at TP GPP was strongly and positively correlated with T_{\max} and especially VPD in early-spring

and negatively during summer. Such correlation patterns of VPD with GPP also occurred in OJP.

At long-term scale, carbon sequestration at tracheid scale and ring level presented significant correlations with climate variables in both sites. Overall, temperature and VPD showed a positive effect on CWA and RWA at the beginning of the growing season, and then shifted to negative in summer, especially for CWA. Specifically, an increase of the negative effect of temperature and VPD on xylem biomass during summer, and of the positive effect of temperature at the start and the end of the growing season (especially with T_{max}). However, we also noted divergent affects of climate on xylem biomass accumulation when analyzing climate sensitivity analysis on subperiods 1970 – 1994 and 1995 – 2019. At OJP, during 1970 – 1994, precipitation was positively correlated with CWA and RWA in spring and early summer, while in 1995 – 2019 we observed stronger temperature signals. In TP, during 1970 – 1994, CWA and RWA were negatively correlated with precipitation in spring and positively in summer, while temperature and VPD showed the opposite pattern (more evident in VPD). In the temperate forest, during 1995 – 2019, xylem anatomical parameters were positively correlated with precipitation in spring and summer, while temperature presented a positive effect at the beginning of the growing season and then shifted to negative. This pattern was very evident for VPD effect on RWA, passing from positive in spring in the first period to negative in summer in the second period. This work will help to reduce uncertainties and skewed interpretations of models of carbon accumulation dynamics, opening new perspectives in the study of forest carbon cycle.

Upside down and the game of Carbon allocation

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Non-structural carbohydrates (NSCs) represent the primary carbon(C) reserves and play a crucial role in plant functioning and resilience. Indeed, these compounds are involved in the regulation between C supply and demand, and in the maintenance of hydraulic efficiency. Non-structural carbohydrates are stored in parenchyma of woody organs, which is recognized as a proxy for reserve storage capacity of tree. Notwithstanding the importance of NSCs for tree physiology, their long-term regulation and trade-offs against growth were not deeply investigated. This work evaluated the long-term dynamics of mature tree reserves in stem and root, proxied by parenchyma features and focusing on the trade-off and interplay between the resources allocation in radial growth and reserves in stem and coarseroot. In a Mediterranean beech forest, NSCs content, stem and root wood anatomy analysis and eddy covariance data were combined. The parenchyma fraction (RAP) of beech root and stem was different, due to differences in axial parenchyma (AP) and narrow ray parenchyma(nRP) fractions. However, these parenchyma components and radial growth showed synchronous inter-annual dynamics between the two organs. In beech stem, positive correlations were found among soluble sugars content and Nrp and among starch content and the AP. Positive correlations were found among Net Ecosystem Exchange (NEE) and AP of both organs. Incontrast, NEE was negatively correlated to radial growth of root and stem. Our results suggest a different contribution of stem and roots to reserves storage and a putative partitioning in the functional roles of parenchyma components. Moreover, along-term trade-off of C allocation between growth and reserve pool was evidenced. Indeed, in case of C source reduction, trees preferentially allocate C toward reserves pool. Conversely, in high productivity years, growth represents the major C sink.

Monitoring the wood formation of black pine trees to understand the historical fire seasonality in Türkiye

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Fire seasonality is one of the fundamental parameters to describe the fire regime of a region and also can be used to develop policies for fire management strategies. This fire regime parameter is still uncertain in pyrogenic forest ecosystems, which increases the importance of the need for more studies on the seasonality of fire. The most common used method for determining the fire seasonality in tree-ring-based fire reconstruction studies is based on following the position of the fire scars during a growth year. However, this classical method is highly subjective and also does not suitable for all types of tree species and regions. In order to understand the seasonality of a fire year, we need more precise estimations using the wood formation process. Therefore, the earlywood and latewood formation processes can be determined by monitoring the intra-annual wood formation processes during the vegetation period to obtain information on in which months the fires occurred. Our previously published multi-century-level fire history reconstruction showed that fire seasonality in Western Anatolia remained unchanged and the majority of the historical fires occurred in the latewood formation period. For this reason, we analysed the cambial phenology of the trees to determine the wood formation timing in order to determine the early and latewood formation periods. We collected microcore samples monthly during a growing season (April – November 2021) from four sites that were near the previously studied fire history reconstruction sites. These study sites are located in a climate gradient from the north (KIR site; the Black Sea climate in Bolu) to the south (HAV site; the Mediterranean climate in Isparta), and one additional site was sampled in Kütahya (KUTL and KUTH; the Marmara transition climate) to represent the elevation differences. The imagery of stained microsections was used to count the four cell development phases and, later, the total of standardised enlarging, thickening, and mature tracheid cells were modelled by fitting a Gompertz function. We also measured the wood anatomical traits (cell wall thickness and lumen diameter) to classify the earlywood

and latewood cells based on the Mork index. Our results showed that the latewood tracheids formed between August (July in Isparta) and November, thus, suggesting that most of the fires in western Anatolia occurred during the late summer and fall. As it is expected that latewood cell production starts one month earlier in the south than in the north. We also observed noticeable xylem growth differences among sites (the highest and the lowest in high and low elevation sites), which might be related to the effect of elevational differences. We found that the earlywood formation period was longest in the KIR (northern site) and shortest in the HAV (southern site). This difference in the length of the earlywood formation period shows the significant control of climate and latitudinal effects. The gathered knowledge can be useful to better interpret fire seasonality for our region and used for more effective fire management activities or plans by fire managers. This data, on the other hand, can lead to other studies on wood kinetics, plasticity, and seasonality reconstructions as a new proxy to advance our long-term knowledge.

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Impacts of the trophic cascade via avian predators on tree growth in temperate beech and oak forests

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In recent years, global warming significantly impacts forest ecosystems in the temperate climate of central Europe. Frequent summer droughts stress the resilience even of well adapted forest species. Natural pest control along the trophic cascade in managed forests could positively affect tree resilience and productivity. This hypothesis is based on findings that relatively even-aged forests provide too little opportunities for cavity-nesting birds, thus reducing predation of leaf-eating caterpillars. In this study, we investigate whether this top-down control cascades into the next level and impacts on tree vigor. In a field experiment, we reduced caterpillar abundance by mounting nest boxes for birds in two forest sites. Caterpillar abundance was estimated based on the collection of frass drops under dominant beech (*Fagus sylvatica*) and oak (*Quercus* sp.) trees. On average, the nest box sites revealed a reduction of caterpillar abundance by 32% (2021) and 52% (2022) compared to the control sites. There was also less (44%) caterpillar induced leaf damage, estimated as the reduction in leaf area from canopy branches in 2022. Trees responded to these alterations only in 2022, when high differences in caterpillar abundance coincided with a prolonged summer drought. Stem radii recordings from point dendrometers increased significantly more at sites with decreased caterpillar abundance over the turn of the growing season. Stronger growth occurred particularly during weeks with pronounced differences in caterpillar abundance. Diurnal variations in stem radii at sites with high caterpillar abundance are slightly higher than expected. This may indicate an increased stem water deficit potentially related to enhanced leaf damage. Monitoring is continued during the upcoming growing season. If our results are confirmed, maintenance and cultivation of bird populations should be acknowledged as a key aspect of ecosystem stability and forest management.

Growth and development of sessile oak trees affected by local industrial pollution in Copșa Mică

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Industrial pollution is one of the factors contributing to the degradation and even drying out of some forest ecosystems and to the amplification of climate change. Knowledge of the mechanisms and effects of pollution on forest ecosystems is therefore an important component of their management plans. Air pollution can alter the normal growth behaviour of trees, both in terms of growth dynamics and response to environmental changes. This study provides an analysis of the impact of local industrial pollution in the Copșa Mică region on sessile oak trees. The sampling method was designed to capture trees affected to different degrees by industrial pollution, thus obtaining three degrees of pollution damage (intensively polluted area, moderately polluted area and unpolluted area). The growth series of trees affected by different levels of local pollution showed that trees show different growth in relation to the level of pollution. The resilience indices showed that trees in the highly polluted area had lower growth than those in the moderately polluted and unpolluted areas. The resilience indices showed that in the period 1985-1995, trees in the highly polluted area had high resilience values, indicating that they had managed to recover the growth lost in the previous period. The dendroclimatic response of the trees shows that sessile oak was positively influenced by precipitation for most of the period analysed. However, temperatures had a negative effect on tree growth in the period April-September. The dendroclimatic response of the trees differed in relation to the degree of pollution damage. Correlations with climate variables over moving periods revealed that trees in the intensively and moderately polluted area showed a different pattern in the period 1970-1990 compared to trees not affected by local pollution.

Thinning improves growth and resilience after severe droughts in *Quercus subpyrenaica* coppice forests in the Spanish Pre-Pyrenees

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During the past years, growth and productivity of different oak species have been constrained by water shortage in seasonally dry regions such as the Mediterranean Basin. Thinning could improve oak radial growth in these drought-prone regions through the reduction of tree competition for soil water in summer. However, we still lack adequate, long-term assessments on how lasting are thinning treatments effects and to what extent they contribute to oak growth recovery after drought. Here we aim: (i) to study the radial growth sensitivity to drought of *Quercus subpyrenaica* in the Spanish Pre-Pyrenees, and (ii) to verify if thinning represents a suitable option to enhance growth resistance to drought and post-drought growth recovery. We analysed basal area increment (BAI) trends in the period 1960-2020 of formerly coppiced oak stands thinned in 1984 and compared them with unthinned plots and also with coexisting Scots pine (*Pinus sylvestris*) growing in thinned plots. We used the Standardized Precipitation Evapotranspiration Index (SPEI) to estimate the severity of droughts and we also assessed climate-growth relationships. Oaks in thinned plots showed higher BAI (369 mm²) than those in unthinned plots (221 mm²). Growth rates remained higher in thinned than in unthinned plots also under intense drought stress. A severe summer drought in 1986 caused abrupt BAI reductions in both oaks (- 40.5%) and pines (- 40.1%). The positive effect of thinning on growth lasted for over 20 years and slightly declined as canopies closed. In the thinned plots, trees with smaller diameter showed the greatest growth release. Oaks in unthinned plots and Scots pine were more sensitive to short-term droughts in terms of growth reduction than oaks in thinned plots, while long term droughts have similar effects on oaks from both thinned and unthinned plots. Oaks were resilient to drought, showing recovery periods lasting from 1 to 2 years in both thinned and unthinned plots. However, intense and prolonged droughts could strongly reverse the expected growth enhancement of thinned plots, and a greater frequency of droughts would limit coppice growth and productivity thus lengthening the rotation periods.

Species-specific growth responses to local and regional climatic variability support a diversity portfolio effect in Mediterranean tree assemblages.

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The portfolio effect is one of the principal hypotheses that explain the important effect biodiversity exerts on ecosystem stability. Consequently, in a challenging moment like Global Change, understanding the role of tree biodiversity is of paramount importance in forest ecology. One of the main objectives of this approach is to analyze a potential portfolio effect in our tree assemblage through functional compensation mechanisms. The portfolio effect is one of the main hypotheses that explain the biodiversity-stability relationship. It has been defined as a variance reduction effect of biodiversity on an ecosystem process, so fluctuations in time in high-diversity communities may be much smaller in low-diversity ones. The other principal aim is to determine which local climatic factors and teleconnections are responsible for the interannual variations in the growth of the tree species studied. We set up our study in a region of the Iberian Peninsula with transitional climatic characteristics that allow the coexistence of needleleaf and broadleaf tree species with a wide variety of strategies and functional traits that allow them to respond differentially to climatic characteristics. A dendrochronological approach was followed to analyze tree growth in relation to climate factors. A total of 176 trees were sampled and analyzed: 40 for *Quercus suber*; 31 for *Q. ilex*; 41 for *Q. faginea*; 24 for *Q. pyrenaica* and 40 for *Pinus pinaster*. We found that the magnitude and sensitivity of the response to climatic variability were species-dependent, especially during climatically extreme years, where the species showed accused tree growth differences indicating compensatory responses. These results point to the existence of a portfolio effect in Mediterranean woodlands that support tree diversity as an effective driver of ecosystem stability. Although the combination of dry and hot years always detriment tree growth, the association of conifer and broadleaved (evergreen and marcescent) species in our study site can have a significantly positive influence dampening their effects by complementary traits and responses.

The effect of a dry growing period on the seasonal dynamics of European beech and Norway spruce in the South Moravia region, Czech Republic.

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The frequency, seasonality and severity of heat waves will certainly increase as a result of ongoing climate change, raising concerns about the effects of meteorological droughts on forest ecosystems and tree species growth. The year 2018 is considered a reference dry year due to its intensity, and one of the warmest and driest years for Central-Northern Europe countries. In the Czech Republic, the growing period of 2018 was characterized by a warm but not exceptionally dry spring (April-June) followed by a summer drought (July-August). Xylem phenology was observed on microcores of European beech and Norway spruce stem tissues, selected in weekly intervals using the Trephor tools between April and November, at an ecological research station located in the South-Moravia region. In total twelve healthy, dominant or co-dominant mature trees (6 trees per species) aged about 130 years were randomly selected on the site. As expected the beech trees displayed the highest growth rate but the shortest growth duration. Onsets of cell differentiation phases occurred in the same period, from the last week of April till the beginning of May. The maximum rate of xylem cell production occurred in the second half of May for both species, with a week delay for Norway spruce. The duration of xylem growth (i.e. the cessation of secondary wall thickening minus the beginning of cell enlargement) was 162 and 99 days for Norway spruce and European beech, respectively. This study did not confirm a severe influence of the dry and warm summer of the year 2018, possibly due to the preceding wet spring or the moderate dry conditions based on the Standardized Precipitation Drought Index ($-1.5 < \text{SPEI} < -1$). Yet, the relative early cessation of the European beech trees or the low number of tracheid cell production of Norway spruce trees could potentially be drought-induced in synergy with the trees' age. A wider xylem growth analysis on the past and next years is being employed.

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Long-term growth decline is not reflected in crown vitality status of European beech after drought

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Global warming poses a major threat to forest ecosystems around the world. In Central Europe, vitality losses and tree mortality have already been observed in various regions, especially after extreme dry spells such as the 2018-2020 drought. Such drought spells are likely to become more severe in future. European beech (*Fagus sylvatica* L.), which is the dominating tree species in large parts of temperate Europe and was found to be relatively drought sensitive, also suffered from the recent drought. In Germany, losses in crown vitality were, for example, observed in the summer of 2019. Interestingly, it was noted that within individual stands, the crown condition of beech trees differed strongly from non- / weakly damaged trees (hereafter referred to as vital trees) to strongly damaged / dead trees (non-vital trees); tree characteristics (e.g., tree social status) and micro-site conditions, however, were apparently similar. To check whether differences in growth behaviour exist and (or) developed over time between the non-/vital individuals, a study was initiated comparing tree ring growth responses and genetic markers in nine forest stands in the northeastern German lowlands and the German Central Uplands. More specifically, (i) statistics describing tree-ring series, (ii) long-term trends in basal area increment, (iii) the climate sensitivity of tree growth, (iv) the resistance of trees to extreme drought, as well as (v) the individual heterozygosity of non-/vital trees were compared. Remarkably, differences between non-/vital trees were generally small with seemingly vital trees, for example, showing long-term growth decline as well. So: Long-term growth decline is not reflected in crown vitality status of beech after drought.

Heading for a fall: predisposition of beech trees to windthrow is detectable in their growth pattern.

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Common beech (*Fagus sylvatica*) is one of the most important deciduous tree species in European forests and is by nature the dominant tree species in most of Western and central Europe. However, according to both empirical and modeling work, climate-change-induced drought may threaten the dominant position of beech, especially in central and southern Europe. The largest beech trees in the world can be found in the Sonian Forest, a UNESCO World Heritage site close to Brussels (Belgium). This site is famous for its high density of very large beech trees thanks to past management, climatic suitability, and unique soil. This soil could be a mitigating factor for some of the negative effects of climate change. Here we investigate the growth of beech using increment cores. Tree ring data was used to evaluate growth trends, response to climate, and the effect of mast years. By sampling 39 living and 16 recently wind-thrown trees, the link between windthrow and precedent growth could be assessed. We found that recently wind-thrown trees, showed a significantly lower growth rate compared to living trees, this difference is already discernible since the 1970s. Although we found differences in growth rate, the wind-thrown trees did not react differently to droughts, heatwaves, or mast years when looking at inter-annual growth changes. All trees were generally sensitive to droughts in spring and summer but recovered promptly after such an extreme climatic event. The overall growth rate trend for the living trees shows a slight decline over the last 50 years, after a peak in the 1970s, but is still in line with growth rates before that time. Notwithstanding the recent increase in extreme climatic events, these old trees still show good resilience, recovery, and a high general growth rate. These results may contribute to the debate on the uncertain future of beech in Europe within the context of global change.

To die or not to die - A tree-ring based assessment of predisposition to drought-induced mortality in European beech

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Climate change, especially via droughts and heatwaves, has the potential to reduce forest productivity and amplify tree mortality rates. One recent examples of climate change type hotter droughts were the severe and long-lasting summer drought of 2018, which triggered a wide-spread increase in tree mortality across Central Europe. With climate change models predicting a significant increase in the frequency, duration, and severity of droughts, there is a clear need to better understand the processes underlying drought-induced tree mortality. One of the heavily affected tree species is European beech (*Fagus sylvatica*), a key species in Central European forest ecosystems, and its sensitivity to drought could have significant ecological and economic impacts.

Here we aim to explore whether a predisposition to drought induced-mortality is connected to changes in tree-vitality caused by changing climate regimes occurring already years before the tree dies. We used a subset of sites from the Beech Drought Network (BDN) established along a climatic gradient in Northern Bavaria in the BEECHDECLINE project. In total, 189 trees from 9 sites were used in the analysis. The specific sampling design in the BDN resulted in two groups of samples for each site: a control group of seemingly unaffected trees and a treatment group of drought-affected trees. We quantified and compared the loss of vitality among trees through a set of decline indicators related to critical slowdown and proximity to mortality such as tree resilience indices and long-term growth decline. Growth indices (ring-width indices (RWI) and basal area increment (BAI)) serve as the basis for all indicators related to above-ground productivity.

Preliminary analysis indicates a decoupling of growth of vital and declining trees after repeated exposure to drought events, but no clear pattern of low growth rates in vital trees favoring higher resilience.

Anatomical response of South Moravian floodplain forest to groundwater alteration and drought

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Drought frequency and intensity has increased in Europe as an effect of global climate change. and led to the forest degeneration and reduced the productivity and vitality. Floodplain forests are particularly vulnerable to drought risks that are exacerbated by both climate change and artificial modification of the river channels to manage floods, resulting in decline of groundwater levels. We studied tree-ring traits (basal area increment, earlywood and latewood vessel lumen area, theoretical hydraulic conductivity, mean hydraulic diameter) to assess long-term adaptations to hydrological stress. The study is focused on *Quercus robur* L. and *Fraxinus angustifolia* vahl. of approximately 120-years-old growing in South Moravian floodplain forest (Czech Republic). The hypotheses of the study were: (i) vessel related anatomical features and hydraulic capacity are closely related to groundwater availability; ii) sites with higher groundwater level show higher plasticity in growth and high hydraulic conductivity as a recovery mechanism.

Tree cores were collected at four sites with different groundwater status but same climatic conditions. Confocal microscopy was used to take pictures of wood anatomical features that were analyzed with ROXAS software. Drought severity was evaluated through calculating Standardized Precipitation-Evapotranspiration Index for 6-month timescale from the continuous temperature and precipitation data during the period of 1960–2017.

The preliminary findings indicate that the growth pattern of *F. angustifolia* responded rapidly to the reduction in groundwater levels, whereas that of *Q. robur* remained less variable and did not exhibit any immediate change in growth. We found significantly higher theoretical hydraulic conductance of oak tree-rings as compared to narrow-leaved ash, confirming their different water use strategies. *F. angustifolia's* more conservative water use made it more sensitive to changes in water availability in terms of radial growth than *Q. robur*. Conversely, the more efficient hydraulic system of *Q. robur* could be at risk due to their lower cavitation resistance under the influence of ongoing climate change. These results suggest that different species-specific anatomical adjustment plays vital role in hydraulic efficiency. Based on our

findings, it appears that the reduction in groundwater availability and the intensification of drought resulting from climate change will pose a substantial threat to these valuable forests.

Growth dynamics of different tree functional types in the Laipuna tropical dry forest

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Tropical dry forests are much less studied than tropical rainforest ecosystems. Due to the distinct rainfall distribution, many tropical dry forest tree species show a clear phenological seasonality which is expressed in leaf foliage as well as in cambial activity. As a result of the periodic cambial dormancy, anatomically distinct tree-ring boundaries are formed in many species. We studied a tropical dry forest in Southwest Ecuador, which is part of the Tumbesian dry forest ecosystem. Wood anatomical analyses combined with other morphological and functional traits allowed a distinction into different tree functional types. Dendrometer measurements run over a period of up to 10 years revealed a strongly different growth behavior between stem succulent tree species (*Ceiba trichistandra*), root succulent species (*Eriotheca ruizii*) and species showing no specific adaptations (*Erythrina velutina*). Leaf phenology had a strong impact on stem diameter curves as recorded by dendrometer dendrometer measurements recorded over 30 minute intervals. Due to leaf flush before the beginning of the rainy season, *C. trichistandra* showed a pronounced peak, followed by a sudden drop in stem diameter, which can be related to initial water uptake and use of water reserves stored in the tree trunk. In contrast, *Eriotheca* showed a stepwise stem increment, with short-term stem diameter fluctuations being buffered by the succulent root system. In climatically extreme years, no net tree growth occurred at all, pointing to the relevance of temporal rainfall patterns besides absolute amounts of precipitation to initiate cambial activity. Despite of the deciduous phenology, tree growth patterns vary distinctly between tree functional types, emphasizing a species-specific analyses of growth analysis before relating the productivity of tropical dry forests simply to precipitation abundance.

Blue rings in trees and shrubs at Europe's most northern treeline in Scandinavia

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The slow growth and high temperature sensitivity of pine trees in northern Scandinavia resulted in some of the world's most reliable climate reconstructions for the past millennia. Recently discovered wood anatomical anomalies that likely reflect temperature-induced reductions in cell wall lignification, so-called Blue Rings (BRs), however, have not yet been investigated systematically in trees and shrubs across northern Europe. Here, we report the occurrence of BRs in 25 *Pinus sylvestris* trees and 25 *Juniperus* spp. shrubs from the treeline ecotone between 280 and 340 m asl in north-east Norway near Iškoras. Exhibiting ages of more than 300 years, both species confirm the occurrence of BRs.

Formation of wood rays in Scots pine based on tree canopy status under hemiboreal conditions

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During extreme weather conditions, non-structural carbohydrates (NSC) are crucial to ensure tree survival and provide ecological plasticity for trees. NSC reserves are partially located in wood rays, which are important elements of the xylem. Additionally, wood rays are essential for water and nutrient transport. During the variable, especially extreme climate conditions, the number of wood rays differs, therefore the quantity of wood rays can be indicative to evaluate the plasticity and adaptive capacity of trees. Scots pine (*Pinus sylvestris* L.) as widespread an economically important tree species in the Eastern Baltic region was chosen for quantitative wood anatomy study.

At the stand level, NSC reserves can depend on the social status of trees which might play an important role in stand stability. Thus, the cores from seven dominant (canopy trees with wide and well-developed crowns) and six intermediate (canopy trees with reduced and narrow crowns) trees were sampled within the commercial Scots pine stand. Tangential anatomical cuts from the outermost 30 tree rings (both early wood and late wood) of Scots pine were taken using a hand sledge microtome to analyze the intra- and inter-annual variation of WRs in stems of Scots pine. Accordingly, the difference between the quantity of wood rays in stem wood of dominant and intermediate Scots pine trees were assessed by quantitative wood anatomy. The measurements of wood ray proxies were made using the WinCELL 2007a software. Linear mixed effect models were implemented to compare the mean values of wood ray's parameters. Time series and correlation analysis were used to identify the correlation between meteorological factors and parameters of wood rays.

The quantity of wood rays mainly differed between earlywood and latewood, meanwhile, the social status of trees expressed a slight effect on the dimensions of wood rays. The size and quantity of wood rays were significantly higher in latewood cells for both dominant and intermediate trees, which might be an adjustment mechanism to cope with weather conditions throughout the season. Additionally, wood rays showed inter-annual variation, which was mainly affected by meteorological factors (temperature, precipitation and drought) in previous season showing the legacy effects of climate conditions on NSC reserves. However, the dominant trees showed higher plasticity by altering the size of wood rays in early wood and late wood and adjusting formation pathways of NSC storage capacity.

Drought-fluctuated tree water balance modifies the seasonality of differentiation and morphogenesis of newly forming phloem cells in Central European Scots pine

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Dynamics of the secondary tissue formation represent physiological responses to meteorological factors affecting tree growth. Seasonality of those tissue traits is affected by ecotype and habitat climate conditions, thus it provides us with a suitable tool to indicate the growth periodicity at specific environments. Cambium bifacially derives both xylem and phloem cells and their seasonal differentiation depends on cambial sensitivity to weather-induced annual variables. While many studies focusing on xylogenesis already proved the climate-growth interactions, the phloem - a crucial transmitter of assimilate synthases, remains as a black box. The seasonal pattern of the phloem formation zones (PZ) varies through particular European regions. Forming annual phloem increment (API) in temperate forests tends to compress the previous API and thus distinguish the interannual boundary. Nevertheless, European climate change variability makes it difficult to recognize. Using cross-section analysis of tree stem micro-cores, we investigated the annual phloem sieve cell differentiation and morphogenesis (from mid-March to mid-November) in Scots pine during two growing seasons (2015-2016) with weather conditions (temperature and precipitation) and tree water status (sap flow) observation. We found the meteorological extremes (heat waves $> 35\text{ °C}$ and drought episodes) as critical limits for cambial division, furthermore to complete the cell differentiation. We proved that cambial activity (CA) is significantly prone to the fluctuation of daily sap flow level (SF). The two-year examination resulted in two different findings. The 3 week-lasting non-precipitation episode and heat wave significantly reduced the SF ($< 10\text{ kg day}^{-1}$) and prematurely ceased the CA. Consequently, the phloem cell production was stopped and the API collapsed into a non-conductive zone for soluble carbohydrates (August 2015). However, during the next year, the improved SF reactivated the CA after the summer drought (in August 2016). Whereas during 2015 the CA was stopped and API already

collapsed in mid-August, during 2016 the API were maintained non-collapsed and conductive, although the new phloem cell production was not observed regardless of reactivated CA. Thus, we managed to demonstrate the trends of phloem morphology adjustment to seasonal meteorological extremes, which might clarify the tree drought-stress responses in a more detailed physiological context.

Mixing wood anatomy, wood formation monitoring and dendrometry on peatland trees: what can we learn?

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Tree population dynamics in peatlands reflect both past environmental history and current climate and land-use changes. At present, increased evapotranspiration or artificial drainage is lowering the water table, which allows for tree colonization. Once established, trees cause further water-table lowering, ultimately leading to increased mineralization and greenhouse gas emissions. Studies aimed at understanding the relations between climatic and hydrological fluctuations and tree growth of peatland trees are therefore of great importance. Yet, dendroecological studies remain scarce and show a complex (hydro)climatic signal in tree-ring widths (TRW), precluding their use for Holocene hydro(climatic) reconstructions. The most common hypothesis arising from TRW analyses is a negative correlation between radial growth and water table increase. However, in the absence of long-term local water table and microclimate records, this assumption still needs to be validated. Here, we developed an innovative methodological framework that combines complementary techniques and dense environmental monitoring in order to disentangle the respective impacts of temperature, precipitation, and water table fluctuations on radial growth. We present preliminary results from four peatland sites located in southern Sweden for which we (1) computed 60-year-long TRW, cell-wall thickness and cell lumen areas chronologies; (2) installed 30 band- and 15 point-dendrometers on trees growing on mineral and peat soils, recording hourly diameter variations for periods back to 2018; and (3) monitored wood formation using microcoring during two growing seasons. We highlight the beneficial aspect of combining invasive methods with non-invasive dendrometry to monitor peatland trees. For instance, dendrometers offer the possibility to extract climatic signals from daily variation in diameter, but are very sensitive to reversible bark swelling during rainy periods, which masks irreversible growth. We demonstrate the advantages of point-dendrometers that better capture irreversible diameter fluctuations compared to band-dendrometers. Microcoring helps delineate growth periods and phenological timings in dendrometer series and aids in the interpretation of wood

anatomical time-series. Our results show differences in the onset of wood formation, climatic response, and growth rate between mineral and peatland trees due to the influence of water table fluctuations and temperature. In particular, monitoring wood formation allows us to better understand climate-growth relationships, to shed light on future carbon dynamics under different hydroclimatic regimes, and open new avenues for using subfossil tree ring and anatomy chronologies.

Remarkably high blue ring occurrence in Estonian Scots pines in 1976 reveals wood anatomical evidence of extreme autumnal cooling

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‘Blue rings’ (BRs) are visual indicators of less lignified cell walls typically formed towards the end of a tree’s growing season. Though BRs have been associated with ephemeral surface cooling, often following large volcanic eruptions, the intensity of cold spells necessary to produce BRs, as well as the consistency of their formation within and between trees still remains uncertain. Here, we report an exceptionally high BR occurrence within and between Scots pine (*Pinus sylvestris* L.) trees at two sites in Estonia, including the first published whole-stem analysis for BRs. Daily meteorological measurements from a nearby station allowed us to investigate the role temperature has played in BR formation since the beginning of the twentieth century. The single year in which BRs were consistently formed within and amongst most trees was 1976. While the summer of 1976 is well known for an exceptional heatwave in Northwest Europe, mean September and October temperatures were remarkably low over Eastern Europe, and 3.8 °C below the 1961–1990 mean at our sites. Our findings contribute to a better eco-physiological interpretation of BRs, and further demonstrate their ability to reveal ephemeral cooling not captured by dendrochronological ring width and latewood density measurements.

Effect of thinning treatment on xylogenesis and phloemogenesis in young pure Norway spruce plantations - A case study from the Czech Republic

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The influence of various silvicultural treatments and stand densities on tree growth response to climate is considered critical in determining forest preservation, particularly during drought episodes. Despite being the most represented and valuable traded wood species in the Czech Republic, Norway spruce (*Picea abies* L. Karst.) is becoming more sensitive to mortality due to its susceptibility to drought occurrences. Therefore, the relationship between forest management treatments, tree growth, and microclimate reactions must be clarified to predict tree survival in the face of ongoing climate change. The presented study investigates the effect of different thinning intensities on xylogenesis and phloemogenesis in the healthy, fully-leaved, and dominant 14-year-old Norway spruce trees (9 in total) growing in three distinct managed plots in the East-Bohemian forest stand. Pre-commercial thinning reduced stand density to 1,800 trees ha⁻¹ (plot A; mild thinning) and 1,300 trees ha⁻¹ (plot C; heavy thinning) in February 2020. Plot B was a control variant with no silvicultural intervention (4,500 trees ha⁻¹). During the same year's growing season, the trees were sampled (micro-cored) to evaluate xylem and phloem formation (2020) every week. Preliminary findings indicate that thinning improves the rate of an overall increase in both xylem and phloem cells, as well as the total number of generated tracheids and sieve cells. The average number of produced xylem cells in control plot B was barely 140 mature cells, whereas plots C and A were found to be 175 and 200 mature cells, respectively. Moreover, the number of sieve cells formed by Norway spruce trees growing in plot C (heavy thinning) was noticeably increased (more than 20 on average), but the average number of sieve cells produced in plot B (control) in the respective growth period hardly exceeded 15 on average. On the other hand, thinning has negligible effect on the timings of the phenological phases of the xylem and phloem formation. Reduced stand density strengthens individual tree tolerance to drought stress, and the magnitude of this differential response varies among the same species along a climate gradient. Based on that and supported by our findings, thinning can help Norway spruce, sensitive to drought, to overcome adverse climate conditions. To attain the best results in total wood production, the intensity of

the thinning strategy must be evaluated, and more research is needed to determine how the canopy density would behave in the years following the thinning application.

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Wood anatomy along the Andes, a latitudinal gradient study on *Nothofagus dombeyi* (Mirb.)

Oerst

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Southern temperate forests have a major ecological importance. Seven type of *Nothofagus* species can be found in these forests, including *Nothofagus dombeyi*, which is one of the three evergreen species that inhabits the southern temperate forests in Chile and Argentina. This species performs a key ecological role, as is a pioneer tree species from the succession of this type of forest. Nowadays, the south west part of the southern hemisphere is being affected by a yearly drought accompanied with high temperatures. This phenomenon has been occurring for more than 10 years and it has proven effect on global climate change. There is a gap of information on native trees physiological functioning and how the drought is affecting the trees species that inhabits these forests. Some of the questions asked are whether the extended drought is affecting this tree species, and how it has responded to the changing climate conditions over the last 30 years. This study aims to approach this gap, working with *Nothofagus dombeyi* and its wood anatomy. This tree species was chosen because of its ecological relevance. Also, because it has presented dieback events in Argentina's Patagonia; however, there is no clear related information on any native species in Chile. The objective was to understand its wood anatomy in a chronological time lapse and observe if a physiological response to the severe drought occurs. Likewise, dendrochronological data for the species was collected. Four Andean populations of *Nothofagus dombeyi* along a latitudinal gradient were used in the analyses. The northern population is located at its northern distribution limit and in order to diminish the anthropological influence on the data, all four populations are located in National Parks. Wood anatomy was studied focusing on vessels and structure, on tangential cuts made out of wood cores. The growing curves for all four populations were also obtained in order to analyse growing tendencies over the last 40 years. The results show that there is a variation along the population's wood anatomy. The northern population has narrower vessels, consistent with a drier climate. The number of vessels and shape changes along the different populations. The growth tendencies for the four populations showed that there are some populations that have been decreasing over the last decades. This could lead to dieback events in these populations. The results obtained could help understand the mechanisms that play a role in the future of this species. It could also be estimated which population is prone to be more resilient to the new challenging climate the world faces. These valuable findings could help us make successful restauration efforts.

Xylem formation patterns from Mediterranean to subalpine climate conditions on Corsica

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The study of seasonal wood formation is essential to understand tree growth responses to climatological impacts. Here we quantify the variability of xylogenesis along an elevation gradient on the Mediterranean island of Corsica, where two native pine species grow in partly overlapping elevation ranges from the upper tree line to sea level. We extracted microcores from 15 *Pinus nigra* Arnold ssp. *laricio* Maire and 20 *Pinus pinaster* Aiton at five sites along an East-West transect from the coasts (10m asl) to the island's central mountain ridge (1600m asl) during bi-weekly sampling campaigns between 2017 and 2019. Generalized Additive Models were applied to detect radial growth differences in elevation, species, and minimum temperatures for growth initiation. Results show that trees in low elevations experienced over two months longer growth periods with lower maximum growth rates than in high elevations. We found a one-month delay for the beginning of tracheid formation between the low, mid, and high elevation belts, but comparable timing for its termination. At sites where both species co-occur, *P. nigra* forms more xylem cells in a shorter time than *P. pinaster*. Trees at the two coastal sites have comparable growing period lengths, but exhibit a time shift of over a month. Minimum temperatures around the time of growth initiation range between 3.1 °C for *P. nigra* and 9.9 °C for *P. pinaster*. These findings reveal the strong inter-specific differences and the high intra-specific plasticity in the growth behaviour of one of the most widespread tree genera in Mediterranean and temperate zones.

How do the interactions of drought, late frost and masting affect stem wood anatomy and diameter growth in European beech?

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European beech (*Fagus sylvatica*) is the dominant broadleaved species in Central European forests but has shown to be particularly vulnerable to the increasingly frequent and intense drought periods observed in the recent decades. Additionally, beech is a species that shows strong masting patterns with high inter-annual variability in seed production that is synchronised over large areas. Such masting events often involve narrow tree ring widths, suggesting a trade-off in resource allocation. Recent studies have shown that especially a combination of drought and masting results in such reduced stem diameter growth. Less is known about potential concomitant effects on stem wood anatomy. Further, stem diameter growth as well as wood anatomy in beech may also be impacted by late frost events.

In order to gain a better understanding of the interplay of effects of drought, masting and late frost on stem xylem growth and wood anatomy, we studied beech trees growing in 13 forest stands in Southwest Germany. Based on thin sections, which were scanned with a microscope, vessels were detected automatically with the software ROXAS. The following measured/calculated parameters were selected for the analysis: Tree ring width, mean and maximum lumen area, mean hydraulic diameter, vessel density, percentage of conductive area and theoretical hydraulic conductivity. Each time series (1962-2013) was detrended and temporal autocorrelation removed. Drought periods were identified based on the SPEI and late frost events based on modelled bud burst dates and daily minimum temperatures. Masting intensity was derived from available data for the region. We built linear mixed models with three categorical predictors (drought [yes/no], late frost [yes/no], masting intensity [none, low, medium, high] as well as all possible interactions for each of the parameters as the respective response variable and compared the estimated marginal means. Models were run with and without tree ring width as a covariate.

Concerning tree ring width, our results confirm those of previous studies, i. e. masting showed a strong impact on tree ring width but especially the combination of masting and drought resulted in a substantial reduction in stem diameter growth. In turn, in absence of masting drought did not result in a significantly reduced tree ring width. Regarding late frost events we saw similar results, including the interaction effect with masting. Consequently, the occurrence of late frost and drought in a year of high masting intensity resulted in the lowest tree ring

width overall. The effects on the wood anatomical parameters were less clear. For instance, mean lumen area was significantly higher in years with late frost events compared to years without late frost, but the opposite was the case for maximum lumen area, which was also lower in drought years, irrespective of masting intensity. For the mean hydraulic diameter, however, the effect of late frost depended on masting intensity while drought did not have any significant effect. Concerning the hydraulic conductivity, a significant effect of the predictors was observed when tree ring width was not considered as a covariate in the model, as there was a strong positive correlation between those two parameters.

Overall, our preliminary results show that while for tree ring width there was a clear pattern of singular and combined effects – with the impact of drought and late frost increasing with masting intensity – these effects do less result in a particular wood anatomical structure. While our study provides a first insight into the (combined) effects of drought, late frost and masting on wood anatomy of beech, we need to carry out further research into the complex processes of wood formation in response to these environmental factors and internal processes.

The imprinting of windstorm in tree anatomy

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Forest disturbances cause a dieback of trees. Forest disturbances are drivers of forest dynamics in primeval or natural forests. So far, tree rings as the cheap and reliable source of information have been used to evaluate disturbance history of the forest. Xylem functional traits are largely controlled by the tree height and contain also information about wood density. The information hidden in xylem traits then offers a new perspective in study of the forest disturbances. In Boubín primeval forest (the oldest forest reservation in Czech Republic), large disturbances occur periodically in ca 150 years. The goal of our study was to reconstruct the vertical development of the forest after the large windstorm and identify potential predisposition of released trees to further windstorms. During 2017-2019 we corred ca 1000 trees killed by windstorm and during consequent bark beetle outbreak. Based on the data collected in the 2017 and 2019 we reconstructed the disturbance history of the entire forest and identified ca 90 individuals for wood anatomy analysis. Specifically, we focused on juvenile trees in the 1860s growing under canopy or in open gaps and fall respectively survive the windstorm of 2017. In this way we have selected major categories that were also sampled at both terrestrial and hydromorphic soils to compare the effect of soil hydromorphism on post disturbance forest development (in the end then 8 categories with 8 trees). Old trees with the age higher than 200 years were sampled as reference trees surviving windstorm in 1868. This group contained both trees that were released and non-released due windstorm and bark beetle outbreak in 1868. Increment cores were splitted into ca 8 cm long parts for anatomy analysis. They were fixed into wooden slices using waterproof glue and cut on the WSL microtome to get planar surface. Prepared samples were then scanned using a confocal microscope and processed in ROXAS to get cell lumen areas and cell wall thickness. First, before the disturbance, released mature trees were strongly limited in their axial growth due to closed canopy. Canopy opening due to the windstorm was then bottleneck in re-initiation of their axial growth. However, not all trees were able to become dominant and were overgrown by neighboring trees, which is clearly visible in production of cells with smaller lumen areas when compared with the other sampled trees. This strongly supports the possibility of repeated releases in the tree lifespan. Released trees produced wood with larger lumen areas than expected in several years following the disturbance. This is in general given by production of wood with different earlywood/latewood ratio than in the previous and following years.

Last but not least, our results do not show the difference in the tracheid size of trees growing at terrestrial and hydromorphic soils. This result implies that re-establishment of the patch occurs at similar times regardless of microsite edaphic conditions. The canopy was re-established in this specific case ca 40-50 years after the previous large windstorm. Our results thus offer a new perspective on the pre- and post-disturbance history of the Boubín primeval forest. Particularly with regard to the development in sensu of axial growth and restoration of forest canopy cover after a landscape disturbance.

Unenriched xylem water contribution during cellulose synthesis modulated by atmospheric water demand governs the intra-annual tree-ring $\delta^{18}\text{O}$ signature

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The oxygen isotopic composition ($\delta^{18}\text{O}$) of tree-ring cellulose is often used to evaluate tree physiological responses to climate, but their interpretation still has gaps due to the complexity of the isotope fractionation pathways. Indeed, the main processes playing a role in defining the final tree-ring $\delta^{18}\text{O}$ signature are located at source water variations, processes at the leaf level, and synthesis of wood constituents. The partitioning of these influences through the growing season and how climate conditions modify such partitioning are questions still to be answered in order to exploit the full potential of long tree-ring $\delta^{18}\text{O}$ series.

In this study, we aim at identifying the contribution of leaf water enrichment and source water on the tree-ring $\delta^{18}\text{O}$ signature by assessing intra-annual variations of $\delta^{18}\text{O}$ along the tree fractionation pathway of larch (*Larix decidua* Mill.). We focus on two sites with contrasting water availability in the Lötschental valley (Swiss Alps) and two consecutive growing seasons (2012-2013). Our approach takes into consideration specific timing of the involved processes with a high spatio-temporal resolution: environmental conditions, diurnal sapflow-derived transpiration rates, $\delta^{18}\text{O}$ analysis of xylem and leaf water, and intra-annual tree-ring $\delta^{18}\text{O}$ measurements coupled with wood formation kinetics. Structural equation models (SEM) were applied to statistically assess the relations among $\delta^{18}\text{O}$ values of the different pathway components. Furthermore, we calibrated mechanistic models of leaf-water and tree-ring cellulose $\delta^{18}\text{O}$ to explore site-specific contributions of the fractionation processes (e.g., Péclet effect and the proportion of xylem-cellulose synthesis exchange [Pex]) and investigated their climatic drivers.

Our results showed that intra-annual xylem water $\delta^{18}\text{O}$ values and transpiration rates differed between sites and years whereas needle water $\delta^{18}\text{O}$ values did not differ significantly between sites (but between years). However, tree-ring cellulose $\delta^{18}\text{O}$ values were more enriched at the dry site resembling those differences observed in xylem water $\delta^{18}\text{O}$. SEMs

reinforced these results since xylem water $\delta^{18}\text{O}$ contributed more to cellulose $\delta^{18}\text{O}$ in comparison to needle water $\delta^{18}\text{O}$, and this effect was more prominent at the dry site. Vapor pressure deficit (VPD) had strong control on the overall leaf water-related ^{18}O -fractionations. However, mechanistic leaf-water $\delta^{18}\text{O}$ models did not indicate a relevant role of the Péclet effect in our study.

Most importantly, mechanistic models of cellulose $\delta^{18}\text{O}$ revealed that Pex was variable along the growing season. Indeed, we found that large parts of the rings were formed under high proportional exchange with unenriched water (Pex) explaining the source water contribution found in the SEM analyses. Furthermore, we observed that the Pex variability was significantly associated with variations in VPD, instead to sink dynamics as previously hypothesized.

Our study suggests that the imprint of the source water signal on the $\delta^{18}\text{O}$ signature in tree rings is highly dominant, particularly during episodes of high VPD, potentially masking signals coming from leaf fractionation processes.

Anatomical measurements of *Juniperus excelsa* wood as a potential hydroclimate archive in the Middle East and North Africa (MENA) region

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The Middle East and North Africa (MENA) is a hotspot for climate change and potential conflict over natural resources. To protect future generations from destabilization and marginalization, governments and land users need to consider the impact of climate change on the management of natural resources and agricultural systems. A few continuous high-quality instrumental data series in MENA start in the early 1900s, but the majority covers only the latter half of the twentieth century. Proxy records such as tree-ring data allow the development of annually resolved paleoclimatic reconstructions to assess climate variability beyond the instrumental period. A variety of tree species, such as juniper, have been successfully used to reconstruct long climate histories for different regions of the world, making it an extremely valuable natural archive of past climate variations. For MENA, the Greek juniper (*Juniperus excelsa* M. Bieb) (JUEX) is a promising species to extend existing instrumental climate records due to its longevity and use in archaeological constructions. We used tree-ring width and wood anatomical measurements of JUEX from a mountain site in Lebanon (2000 m asl) and a mountain site in Turkey (1400 to 1800 m asl) to investigate the dendroclimatological potential of the species. Using Confocal Laser Scanning Microscopy images, we measured cell lumen diameter and wall thickness for the period 1963 to 2020 for six individual trees from Lebanon and 20 from Turkey covering different time spans. Correlation analyses for the same time period were performed between chronologies of wood anatomical measurements developed from ten equally divided sectors across each tree ring, on one hand, and daily as well as monthly climate records, on the other hand. Our findings highlight the potential of wood anatomical measurement of JUEX as a paleoclimate archive in the MENA region. In Lebanon, Lumen diameter size was reduced starting in the early 1990s, consistent with changing rainfall and temperature patterns in MENA, indicating a long-term climate trend reflected by the cell dimensions. Spatial correlations indicate that such climate reconstructions may also improve our understanding of how large-scale ocean-atmosphere interactions impact hydroclimate in the region.

Xylem anatomy as a new tool to investigate the associations between climate, carbon uptake and biomass growth. First analyses in a Norway spruce forest in the Italian Alps

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Forests play essential role in climate change mitigation and adaptation; it is estimated that roughly 30% of man-made CO₂ emissions are sequestered by the terrestrial ecosystems. Therefore, understanding the link between carbon uptake and forest biomass growth is pivotal. However, several studies found an inconsistent link between ecosystem primary productivity, measured with eddy covariance techniques and tree biomass increment. We investigated the complex relationship between climate, carbon fluxes and tree biomass growth using quantitative wood anatomy in a Norway spruce forest in the Italian Alps. We correlated the inter-annual variability of xylem anatomical features in earlywood and latewood with eddy covariance and climate data. Two xylem anatomical traits, the cell wall area (CWA) and the cell number (NUM), were analyzed in ten trees. Our results showed that CWA in earlywood responded positively to winter precipitation while summer temperature influenced CWA in latewood and NUM in earlywood and latewood. CWA in earlywood and latewood yielded mostly marginally significant negative correlations with the eddy covariance gross primary productivity (GPP) while marginal positive correlations were obtained for NUM in earlywood and latewood. The scarce association between GPP and anatomy here could be attributed to problems on GPP assessment due to advective fluxes on sloping terrains. However, missing associations could be related to the storage of photosynthates in non-structural carbohydrate pools, that is, adsorbed carbon was not immediately mobilized and allocated to stem growth, causing decoupling between carbon uptake and biomass (xylem) growth. This calls for further research on an integrated quantification of other carbon storage pools for closure in forest carbon balance.

Climatic influence on tree growth and wood anatomical parameters of *Abies spectabilis* species of the Central Himalaya, Nepal

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Climate change is fundamentally altering the environment in which conifer species live and grow. The climatic influence on tree growth is expected to be high in the Himalayas due to increasing temperatures (0.6 °C per decade), erratic seasonal precipitations and regional droughts. One of the key challenges for biology is to understand how sessile organisms respond to such changes. Understanding the response of a key species to climatic variability is crucial to predict its adaptation, resistance and resilience. The wood anatomical response of a conifer species from Himalayan plants in a changing environment is currently poorly understood. The aim of this study is to determine the elevational adaptation and wood trait plasticity of mature Himalayan Silver Fir (*Abies spectabilis*) trees to climatic variability along an altitudinal gradient in Langtang National Park of Central Himalaya. At each 500 m elevations, tree individuals will be cored to monitor their anatomical traits from the upper, medium and lower limits of species distribution range. This study will provide more detailed knowledge and insights into how climate influence on tree growth and wood anatomical parameters of the studied species. These insights will be crucial to develop long-term strategies for sustainable management of the Himalayan forest ecosystems

Dynamics of cell wall formation of silver fir tracheids: Exploring the sequence of cellulose deposition and lignification using a multimodal imaging approach

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Despite lignin is a key component of wood, the dynamics of xylem cell wall lignification are generally overlooked, which prevents the understanding of its environmental control and blurs the interpretation of isotopic and anatomical signals stored in tree rings. Although the study of xylogenesis has provided valuable insights into cell wall formation, studies often group cellulose deposition and lignin impregnation of the cell wall into a single phase often referred as cell wall maturation. However, whether cellulose deposition and lignification follow the same intra-annual dynamics has not yet been investigated.

This study evaluates the progression of lignification in differentiating xylem cells of silver fir (*Abies alba* L.), with a particular focus on the time lag between cellulose deposition and lignin impregnation of the cell wall. For this purpose, we applied a multimodal imaging approach combining Transmission Light Microscopy (TLM), Confocal Laser Scanning Microscopy (CLSM), Raman microspectroscopy (RM). Microcores collected from five dominant and healthy trees in the Vosges mountains (NE France) were used to obtain transverse microsections for 11 sampling dates regularly spaced along the growing season. These microsections were observed in TLM and CLSM to produce numerical images. The time lag between cellulose deposition and lignin impregnation was quantified by analysing cell counts measured along three radial files on TLM and CLSM images. The time lag between cellulose deposition and lignin impregnation was quantified by analysing cell counts measured along three radial files on CLSM and TLM images. Moreover, we acquired the RM profiles from one microsection in order to identify the correspondence between the autofluorescence signal in the CLSM images and the amount of lignin.

Chemical RM profiles revealed the presence of lignin in the cell walls of mature cells, but also in wall thickening cells, being however absent from enlarging xylem cells and vascular cambium. Wood autofluorescence was associated to two different signals after excitation with 405nm and 488 nm laser beams. The strong autofluorescence in mature and wall thickening cells was mostly induced by excitation at 405 nm, which relative signal intensity showed a high

correspondence with the RM intensity of the lignin band. This enabled us to delimit the lignification zone on CLSM images by combining the signals excited at 405 nm (lignin) and 488 nm (other cell wall constituents). Generalized linear models fitted on wall thickening (TLM) and lignifying (CLSM) cell counts evidenced highly synchronic intra-annual dynamics of wall thickening and lignification, with simultaneous cell-level timings and durations between the two differentiation phases along the growing season.

Our results show that, at the tissue level, wall thickening, and lignification are concurrent in silver fir. At the cell level, lignin impregnation would begin in the middle lamella at the same time cellulose deposition occurs in the secondary wall. Lignin impregnation of the secondary wall may then follow the progression of cellulose deposition, with a very reduced time lag between the two processes. These results suggest a high time correspondence between cellulose and lignin-related traits in tree-ring chronologies, as they would be recorded over similar timeframes.

**Quantitative wood anatomy considering compression wood of Norway spruce (*Picea abies*)
treeline seedlings and branches**

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Global warming has modified the distribution of forests growing at their altitudinal limit, i.e. treelines. It is unclear what drives treeline dynamics under the increasing drought frequency and intensity. While temperature ultimately limits tree growth at treelines, an important driver of treeline dynamics in the period of rapid warming can be the survival of treeline seedlings exposed to droughts. However, as temperature is considered the main factor responsible for treeline boundary, the role of drought sensitivity in seedlings as drivers of treeline dynamics under global warming is poorly understood. Also, although drought periods usually do not impact survival of adult trees at treeline at short-term, they may have impacts on their growth. Certain wood traits and their variation may affect conifer whole-plant functions such as hydraulic safety and water storage, ultimately affecting survival and growth at the treeline under increasing global warming conditions. One of such traits is the presence of compression wood. It is generally assumed that compression wood has low water conduction, so it is usually avoided when studying hydraulic properties. In this study we analyzed the quantitative wood anatomy of *Picea abies* treeline seedlings and branches from adults, considering compression wood. We collected seedling stems at one site in Krkonoše, Czech Republic. As studies in drought vulnerability for adults are commonly performed on branches, we collected branches (similar in size to seedlings) from adults growing near the collected seedlings. For each seedling and each branch, we measured the proportion of compression and opposite wood in cross sections. We separated the most recent compression and opposite wood, and we did wood macerations. We used light microscopy and Image Pro plus software to measure the following tracheid variables: length, lumen diameter, width, and wall thickness. We constructed generalized linear mixed-effects models to estimate and compare means of the mentioned variables between branches and seedlings, and between compression and opposite wood. Intraspecific variability is a necessary condition for adaptations to changing environments, so we also estimated and compared standard deviations. We used Principal Component Analysis to visually identify potential clusters. We found significant differences between branches and seedlings, and between compression and opposite wood. Compression wood comprised nearly half of the tissue produced in seedlings and branches. We found high and greater variability in

seedlings compression and opposite wood compared to branches. Tracheid length and intraspecific wood anatomical variation are important traits to consider to understand drought adaptations, but they are not frequently analyzed. Our study contributed to document these variables in a gymnosperm European treeline species. These are the first results of a starting research project that aims to understand the drivers of treeline dynamics under global warming.

How late spring frosts affect tree-ring growth and wood anatomical traits of European beech in Mediterranean mountain forests?

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Xylem anatomical traits in series of annual tree rings, allow establishing structure-function relationships and assessing species sensitivity to environmental variability. Extreme events such as late spring frosts (LSF) and drought spells are among the main climate-induced disturbances affecting European beech (*Fagus sylvatica* L.) forests, especially in the Mediterranean region. In this study we aimed to i) compare chronologies of tree-ring widths and vessel traits of beech trees located along an elevation gradient and ii) determine the variability of tree-ring traits before and after LSF occurrence. The study sites, located in the Italian Apennines and Spanish Pyrenees, were hit by severe LSF in recent years. We investigated how tree growth and vessel traits varied in relation to indicators of spring frost occurrence, i.e., mean minimum temperatures, accumulated degree days and temperatures anomalies. Then, we checked vessel traits in rings formed right after the frost events and compared them to those measured in non-affected trees. Radial growth reductions ranged from 36 % to 84 % and this negative effect of LSF on radial growth was only detected during the same LSF year. Growth fully recovered within 1–2 years after the LSF. We found a decrease of vessels diameter and surface area, and higher vessel density with increasing elevations. Vessel traits did not provide added values for detecting spring frost sensitivity. In fact, LSF caused the formation of very narrow rings but no-significant differences in vessels traits. Our results indicate a good recovery capacity of European beech and no legacy effects caused by LSFs. However, other xylem proxies (e.g., fiber cell wall) could better detect LSF impacts on wood formation.

Dendroanatomical monitoring of plane trees (*Platanus x hispanica*) in the city center of Mainz, Germany

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Urban trees provide multiple benefits to cities and their inhabitants but are subjected to a wide range of stressors, including the effect of urban heat islands which exacerbate climate warming, threatening the health, stability and survival of many urban trees. Plane trees (*Platanus x hispanica*), represents the main tree species in the city center of Mainz (Germany), particularly near the Rhine river. We present the initial results of a monitoring campaign conducted in 2022 aiming at 1) assessing recent trends in tree growth in plane trees located in the city center, 2) identifying dendroclimatic signals in plane trees, and 3) quantifying wood anatomical variability in trees showing different responses to environmental stressors and microsite conditions.

We sampled 62 large individuals (mean DBH = 70 cm, range 42 – 102 cm) and produced a chronology of basal area increment for the period 1909-2021. Sampled trees showed a declining growth trend starting from the early 2000s, although no clear signs of crown damages were observed. Clusters analysis allowed to identify groups of trees showing climatic sensitivity to a broad range of climatic conditions, the most frequent ones being late summer minimum temperature, February-March maximum temperature, winter (positive correlation) and spring precipitation (negative correlation). Wood anatomical analysis were also performed to identify differences in the trees' hydraulic structure in relation to different levels of soil availability and distance from the Rhine river.

This research will produce high-resolution, spatially distributed information about growth and health status of large plane trees, providing evidence-based guidelines to support decision makers in assessing risks for public safety and developing effective management plans for the preservation of these historically and culturally relevant trees.

Xylem functional traits driving tree growth and climate sensitivity in sessile oak (*Quercus petraea*) at its southernmost distribution limits.

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To understand how forest ecosystems may respond to future anthropogenic climatic change, in particular to extreme hydroclimatic events, the mechanisms linking tree hydraulic functioning to secondary growth, and how such mechanisms influence trees' response to climate, need to be specified. A multi-proxy approach, targeting traditional dendroclimatic proxies (i.e. ring-width) as well as parameters derived from quantitative wood anatomy or xylem isotopic composition, may greatly improve our capacity to elucidate climate-growth relationships at multiple temporal resolutions. Such a task is particularly important in populations growing at the edges of species' physiological limits, to estimate ecosystem shifts in response to climate change. We developed 298 years-long chronologies of ring-width and basal area increment (BAI), vessel parameters, measures of theoretical hydraulic conductivity, $\delta^{13}\text{C}$, and intrinsic water use efficiency (iWUE) for an old stand of sessile oak (*Quercus petraea* subsp. *austrotyrrhenica* Brullo, Guarino & Siracusa) located in the mountains of Aspromonte (southern Italy), covering the period 1720-2018. The aim of this work was 1) to quantify high-resolution climate-growth/anatomy relationships using daily climatic data; 2) to assess high- and low-frequency common fluctuations between time series of BAI, wood anatomy, and iWUE by analyzing their spectral properties; 3) to retrospectively evaluate short-term changes in xylem hydraulic architecture during disturbance-driven episodes of growth release or suppression.

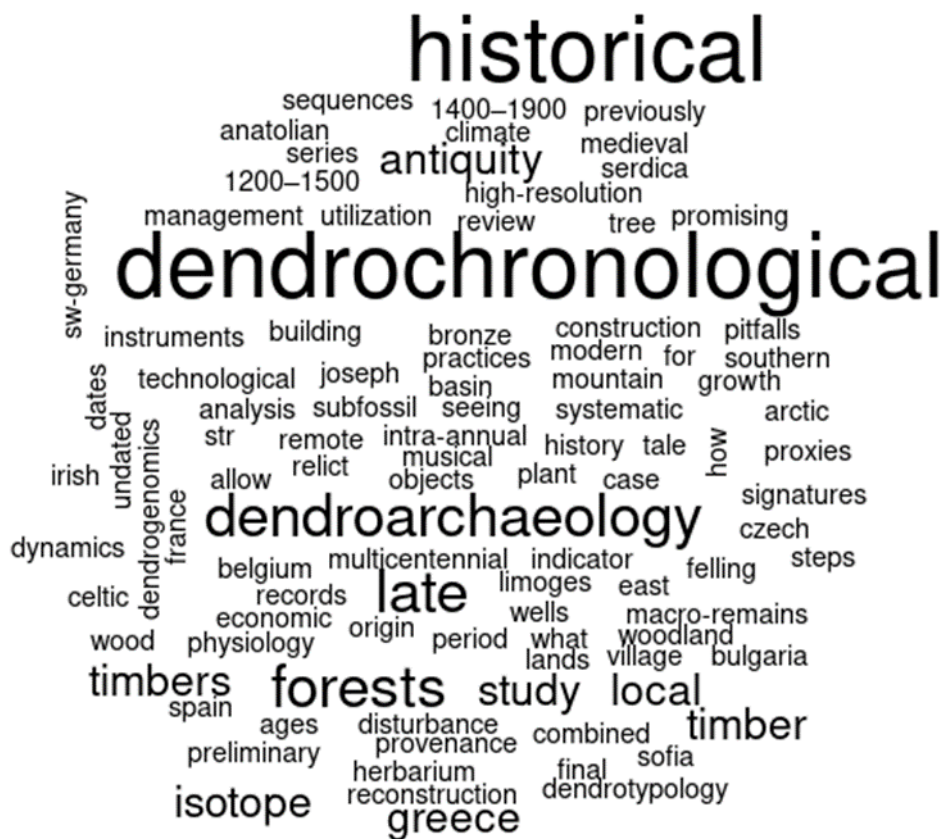
BAI and xylem anatomical traits showed strong correlations with different climatic parameters and during different periods of the year, with secondary growth being driven mainly by precipitation in the early summer, and xylem hydraulic traits responding in general to maximum temperature in the spring. Even if BAI and xylem functional traits did not show interannual correlation, significant coherence between time series of BAI, iWUE, and vessel size emerged over periods of 6-8 years. In the low frequency spectrum, BAI was positively

associated with traits related to xylem vulnerability (i.e. Carlquist vulnerability index), which were also the traits showing the highest relative increase (decrease) during phases of growth release (suppression), suggesting that higher growth rates come with higher risk of hydraulic failure. Our findings highlight the potential of high-resolution multi-proxy analysis of tree-climate interactions and variability in xylem functional traits as a promising approach to upscale morphological responses observed at the microscopic level in woody tissues from the individual to the forest-level.

Historical and Fossil Wood session

Moderator

Julia Weidemüller, Bayerisches Landesamt für Denkmalpflege, Germany



Multicentennial dendrochemical series and dendrogenomics of relict forests in Southern Spain can reveal origin of previously undated historical timber

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Southwestern Europe hosts a big number of UNESCO's World Cultural Heritage objects, chronologically spanning from periods of Great Phoenicia until the end of the Reconquista and later. Wooden remains and artefacts from archaeological excavations as well as material from monumental buildings serve as perfect objects for dendrochronological investigations, from exact calendar dating to identification of wood geographical origin. However, due to the complex interaction between historically varying leading cultures in the area and intense forest use and circular timber exploitation, the correct interpretation of dendrochronological data, namely tree-ring width series, remained challenging. Here we present results of integrated dendrochemical, dendrogenomic and dendrochronological analyses from intensively exploited Cazorla national park and several previously dated and undated historical buildings.

Dendrochronological study of roof beams from the Jaen Cathedral (built in the 16th -18th centuries) revealed that timber from the Cazorla natural park was used in their construction. However, given the area of the park, it remains unknown the exact timber source origin. Moreover, supposedly reused samples (originating possibly from lower elevations) of the Cathedral remain undated due to the lack of tree-ring series covering the felling period.

The Colegial del Salvador church in Seville is a great example of the necessity of the use of additional wood analyses techniques to understand the history of the building. According to archives it was built in 1679 and 1712, but precise dendrochronological dating has failed in the vast majority of samples, suggesting different sources of timber from different periods. The latter is documental supported describing a mosque that was standing on the same spot as the church before the arrival of Christians. The pilot dendrochronological attempts on timber source identification from Hospital Real de Granada (1511-1525) have shown that high

elevation area of the Cazorla park was likely the origin of timber, whereas material from Castillo de La Calahorra was found to be from Natural Park Sierra de Baza and dated to 1950s. Our results confirm that the use of wood chemistry and dendrogenomics methods can overcome the problem of lack of long tree-ring width chronologies, especially from lower elevations. The heavier elements (Strontium and Manganese) and their ratio with structural elements (e.g., Calcium) also allowed pinpointing the origin of already dated timber. Moreover, high diversity in genetic population structure of existing relict black pine forests in Andalusia have shown a great potential for dendroprovenancing studies to discriminate between areas with strong exploitation history but lack of long-term tree-ring width chronologies.

The archaeological plant macro-remains of Serdica during the Late Antiquity: a case study from 35 Exarch Joseph Str. (Sofia, Bulgaria)

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The combination of rescue archaeology and urbanised contemporary areas is not always successful; this is particularly valid for the archaeological plant macro-remains. However, this is not the case at 35 Exarch Joseph Str. (Sofia, Bulgaria) where both carpological and wood remains were well-preserved and are currently under study. The archaeological site at 35 Exarch Joseph Str. falls within Serdica's north fortification system, dated between the 2nd c. AD and the 6th c. AD and its subsidiary wall (proteichism) dated to the 5th c. AD. The excavations recovered assemblages of charred and waterlogged plant macro-remains recorded from several phases of occupation. The earliest period (2nd – 3rd c. AD) captures a ditch and architectural remains, followed by a period signatred by wooden building (3rd – 4th c. AD) and a coin hoard dated to 320 AD; the latest phase (5th – 6th c. AD) is characterised by stone sewage with a brick-layered floor. This multi-layered occupational activity left numerous remains of wooden architecture: building elements of both deciduous (deciduous oak, willow, hazel etc.) and coniferous (fir, pine and spruce) species, raw of conifers (fir and pine) with undetermined function, wooden objects related to the everyday life during the Late Roman period and the Late Antiquity and a large anthracological assemblage recorded in the fire-related structures and the destruction contexts. In addition, representative archaeobotanical data enhanced our knowledge of the utilisation of tree species during the studied period, including the vine, olive, sweet cherry, sour cherry, plum and walnut. Our presentation will attempt to tile the puzzle of the diverse plant-macro remains data of 35 Exarch Joseph Str. It will do so by offering taxonomic results, placing them in contexts with a proposed interpretation and adding a preliminary dendrochronological approach based on measured tree-ring series of one of the best-preserved construction elements of fir.

Dendrochronological investigation of subfossil yew trees from the east of England

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Tree-ring chronologies form the backbone of high-resolution palaeoclimatology. They provide annually resolved and absolutely dated temperature and hydroclimatic reconstructions spanning past centuries to millennia. However, the number of tree-ring records prior to Medieval times declines drastically, and there are only a few chronologies extending more than 4000 years back into the mid-Holocene.

Here, we present an assessment of more than 300 subfossil yew (*Taxus baccata*) trees excavated from around sea-level peat-rich soils in the Fenland of coastal southeast England. The well-preserved trunks are two to eight meters long, often exhibit adventitious roots, and contain up to 400 rings of irregular growth.

Initial radiocarbon and dendrochronological dating has produced three floating ring width chronologies that span more than 1000 years between 5400 and 4200 cal BP.

Our preliminary findings show an unexpected potential of subfossil Fenland yews to improve our understanding of climatic trends and extremes over the mid-Holocene, including the still debated 4.2 ka event. Moreover, we expect our data to facilitate the dating of archaeological remains, refine sea level reconstructions around the British Isles, and improve the resolution of the international radiocarbon calibration curve IntCal.

An exceptional roman well from a Villa Rustica at Kerpen-Manheim, Western Germany

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Caused by open cast lignite mining activities, it was possible to excavate large parts of a Villa Rustica (HA 162) and to examine it extensively. In addition to three large buildings within a rectangular ditch, two wells, each of which showed wood preservation, were discovered. From the archaeological point of view activities at this area started in the first half of the 1. century CE. However, its heyday dates to the first half of the 3. century CE, while its end dates to the 5. century CE.

One of the two discovered wells stands out for its construction and the finds contained in its backfill, both from an archaeological and dendrochronological point of view. The upper part of the well was made of sandstone blocks in opposition to the bottom, which was built out of wooden boards arranged in two nested cask-like constructions. For both, the outer as well as the inner construction, a tongue and groove technique was used. However, the boards of the outer construction were made of *Pinus sylvestris* and the tongues of *Quercus* spp. The inner construction was made entirely of *Quercus* spp. In total, the outer construction provided 17 boards and 17 tongues, while the inner one provided 21 boards and 13 tongues.

Our presentation focuses on three aspects: Firstly, we present a dendrochronological dating of both wooden cask-like constructions and discuss their relation to dating based on archaeological finds, which will give insights into the duration of use of the well. Secondly, we investigate whether the *Pinus sylvestris* boards of the outer construction could have been stem-identical. Therefore, we have sampled all 17 boards two times on both ends and apply statistical parameters combined with optical indications like branches. Finally, we examine the possible provenance of the *Pinus sylvestris* boards and discuss its implication for land use during the roman period in the Rhineland.

Irish Dendrochronological Research: The Final Countdown

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The Belfast tree-ring laboratory was set up in the 1968 to construct a long oak tree-ring chronology to provide wood samples for the radiocarbon calibration exercise. A bonus of this exercise was that if dendrochronologists used timbers from building or archaeological sites in the chronologies then the dates obtained would be of interest to historians and archaeologists. The 7500-year oak chronology also provided greater clarity of the timing of past environmental and human activities. New approaches that enhance the dating and interpretation of the tree-ring chronologies from Ireland are being used. These include the use of stable and radio-isotopes to facilitate the dating of problematic samples and floating chronologies from short-lived species. The construction of the Belfast Long chronology was completed in 1984 under strict dendrochronological conditions. A lot of long-lived, measured oak samples from various buildings from Ireland were not included in the master chronology. Many of these samples have now been dated and indicate an importation of quality timbers from continental Europe. The construction of the Eastern Baltic oak tree-ring chronologies has provided chronologies that can be used to dendrochronologically date many of these previously undated samples. This presentation will examine the dating and probable origin of many of the European timber samples found in Irish building.

Dendroarchaeology in Greece - from humble beginnings to promising future

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It was back in the early 1960s when Bryant Bannister recognized the dendrochronological potential of Greece. More than two decades later, in the late 1980s, P.I. Kuniholm, together with C.L. Striker, started collecting and analyzing tree-ring series from several historical buildings, forests, and archeological sites in Greece and the surrounding Aegean region. Despite highly promising results compiled especially from the northern and western parts of the country, dendroarchaeology did not attract much attention in the coming decades. It was only by the end of 2000s dendroarchaeology was reintroduced; first in Crete through the Cretan Dendrochronology Project, launched by T. Ważny, J. Moody, and O. Rackham, and then by another independent project concerning the restoration of a historical building on the Euboea island, where the architect in charge, E. Tsakanika collaborated with T. Ważny to date a Venetian building and reveal its different phases of construction. Such isolated case studies became much more common over the last five years within the framework of the Balkan-Aegean Dendrochronology Project: «Tree-Ring Research for the Study of SE-European and East Mediterranean Civilizations» (BAD project). Dendroarchaeological surveys have been conducted both in historical buildings and archeological sites throughout Greece with an emphasis on regions previously ignored, such as the southern part of the country and the islands. Priority was also given to buildings under restoration, since in such cases original timbers were usually much more accessible and the architects and archaeologists in charge were more willing to collaborate. Our goals were not just to date available timbers or provide information about the species used or the possible origin of the wood, but also to help end-users realize the importance of this information and how dendroarchaeology can contribute to the reconstruction of the local history and the protection of cultural heritage. Meanwhile, the analyzed tree-ring series permitted us to develop new, well-replicated chronologies that may be used as references for further dating of historical timber in the future and for applications of tree-ring research in other fields such as environmental studies. The BAD project will end in 2023, but our interest to explore what old timber can tell us about environment and human past will continue.

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Critical steps in dendrochronological analysis of musical instruments and other historical objects

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Dendrochronological analysis of musical instruments is used to determine the age, origin, maker or maker's school, and finally the authenticity of the instrument. The aim of this study is to focus on some critical steps of dendrochronological analysis of a violin. The analysis is performed on a top plate, which in most cases is made of Norway spruce (*Picea abies*) and is composed of two boards glued together. The tree ring measurements must be made in an absolutely non-destructive way on the radial surface, where the tree rings appear as bands. The tree rings are usually narrow with narrow and pale late wood and are often difficult to detect. This is further complicated by aging of the wood, dark and opaque varnishes, and damage, repairs, or dirt on the surface. Since it is recommended that tree ring width measurements be made on images, we will discuss the advantages and disadvantages of various image acquisition techniques. Once the measurement is complete and a mean curve has been established based on tree ring series from different parts of the board, we can proceed with dating. Dating is another critical step for which we need appropriate reference chronologies. Few chronologies suitable for dating violins are publicly available in the International Tree Ring Data Bank (ITRDB). Therefore, laboratories invest a lot of effort in creating their own chronology collections. Only a few highly specialized laboratories have chronology collections that cover geographic areas of presumed wood origin as well as dated instruments associated with specific instrument makers. Chronologies should ideally cover the last five centuries, when the majority of valuable historical and modern instruments were made. Establishing long chronologies based on trees and historic wood from the same area is particularly challenging due to the lack of old trees and suitable historic objects to extend tree-ring series into the past. The dendrochronological dating provides the end date, i.e. the date of the outermost tree ring. The dendrochronological end date almost never coincides exactly with the year in which the instrument was made. It must be considered as a terminus post quem, i.e., the year after which the instrument was made. This means that we must estimate Δt , which indicates how many years must be added to the end date to determine the possible date of manufacture. We estimate this using information about how many years it took to transport, dry, and store the wood, and how many tree rings were removed during wood

processing. The literature gives a range of Δt from a few years to a few decades, with Δt generally larger when tree rings are narrow. Since dating is usually performed with a set of reference chronologies, the values and significance of the statistical parameters allow conclusions to be drawn about provenance, i.e., geographic area, instrument maker, or school of manufacture. Tree-ring dating and provenance determination of musical instruments is still mainly based on the measurement of tree-ring width. Although the introduction of other tree-ring related parameters such as latewood density, wood anatomical and wood chemistry time series, DNA profiles, and the combination of different methods have yielded promising results in improving dendroprovenance, it will take some time before networks of reference chronologies are established for geographic areas and time periods of interest. Similar challenges with specific peculiarities apply to furniture and other historic objects.

How local is local? Ring-width sequences and strontium isotope ratios of Limoges' construction timbers allow to delve into the history of domestic forests of Central France

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Like many other cities in Europe, Limoges (Central France) has relied for centuries on timber products for construction but also on firewood for heating and crafts. Archival sources report the intensive exploitation of the forests located to the northeast of the city and the floating of wood to the city through the rivers Taurion and Vienne. However, the documents analysed thus far never directly mention construction timber and suggest that the floating was done by drifting rather than rafting. Oak (*Q. robur* and *Q. petraea*) is the dominant species in the area, and its floatability is traditionally questioned by scholars. Therefore, given the lack of written sources about the provenance of construction timber, we decided to study extant historic buildings in Limoges with the aim (1) to precisely locate the origin of construction timber by coupling dendrochronological and geochemical methods, and (2) to use the information to elucidate timber supply strategies and the forest history of Central France.

The matching of tree-ring patterns has been used for decades to locate the origin of wood (i.e. dendroprovenancing). Nevertheless, master and site chronologies are often built using material found on site but whose provenance is yet unknown, and the traditional statistical approach based on *t* values has several pitfalls. For this reason, several authors have recently decided to test and couple different provenancing proxies such as wood anatomy, stable isotopes and DNA markers.

Three years of dendrochronological studies conducted on 212 wooden elements from Limoges' vernacular houses have provided a 419-year-long tree-ring chronology spanning from 1317 to 1753. The research has revealed that a substantial number of the houses studied are dated to the second half of the 15th-century, indicating an intense construction activity during that period. While the regional provenance of the wood could be established by

dendrochronology, we analysed the $87\text{Sr}/86\text{Sr}$ signatures of the historic timbers to increase the spatial accuracy of the dendroprovenancing analysis. The Sr ratios obtained from the historic timbers were compared to those obtained from living trees and historic structures located in areas that potentially supplied the city in the 15th century. Here we present the first results of our multi-proxy timber-provenance study and discuss them in the context of the forest history of Central France.

A tale of an orthodox church in a remote mountain village in Epirus, NW Greece

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The current study is a dendroarchaeological examination of an orthodox church, located in a remote village called Pades in Northwest Greece, a few kilometers from the Greek-Albanian border. The village is built on the slopes of Mt. Smolikas (2637 m a.s.l.), the second highest mountain of Greece and falls within the borders of the Northern Pindus National Park, the largest terrestrial national park in the country. The first written reference to the village of Pades dates back to 1692.

The Church of the Assumption of the Virgin Mary is a stone building rectangular in plan with an apse on the east side. It has the form of a basilica with nine irregularly arranged windows and two entrances. According to the inscription at its entrance, the church was built in 1784, but there are many indications that some parts of the church may be older. Dendrochronological study of the building was necessary to clarify the construction history of the church, but also to develop long and well-replicated historical reference chronologies, especially for the mountainous regions of Northwest Greece that have not been sufficiently explored thus far.

The construction of the church standing today was carried out in phases, probably due to economic reasons and difficulties with finding the required building materials. One important aim of our study was to determine the construction date of the walls of the church. This was possible thanks to oak slats and round logs, which provided the walls with the flexibility and resilience required in seismically active areas. Our dendrochronological analysis concluded that the final year of the wall construction was 1792. This is later than the date, the year 1784, mentioned in the inscription at the entrance, which probably refers to the inauguration of the complete rebuilding of the church.

According to our results, roof construction took place in the years 1804-1809. Under the cover of a new roof a wooden barrel vault was constructed over the central nave in the years 1812-1814. The time intervals represent the periods of harvesting, transportation and

seasoning of wood followed by carpentry work, which probably lasted only a few months. The two beams on both sides of the entrance door inside the southern wall indicate the need to build or rebuild the entrance directly to the nave of the church, which must have taken place after 1825. We also reconstructed the dates of the 19th-century repairs to 1855 and the last repair of the floor after 1859.

The species used for the construction of the church are mostly black pine (*Pinus nigra*), Bosnian pine (*Pinus heldreichii*) and oak (*Quercus sp.*). Both Black and Bosnian pine represent most probably local timber, as suggested by the perfect cross-dating against chronologies representing regions of Grevena, Smolikas, or Pindus. The Bosnian pine timber was definitely of local origin and transported from a nearby forest – not more than 80 km from Pades. Due to the topography of the area, it was possible to harvest trees and transport them only within a limited area. A few oaks used exclusively inside the walls originate probably from the lower-altitude forests near Konitsa or areas closer to the Greek-Albanian border.

Dendrochronological study of the church in Pades yielded three new tree-ring chronologies: Bosnian pine covering 1260-1826, black pine covering 1295-1854 and oak chronology covering years 1507-1767. Reused timbers from the 15th and 16th centuries reveal a much longer history of the church than the oldest records known from the village of Pades.

This research was funded by the National Science Center, Poland, project nr 2016/22/A/HS3/00285. The examination of the wood samples has been performed under the required permission from the Ephorate of Antiquities of Ioannina and the Hellenic Ministry of Culture and Sports (ΑΔΑ: 9ΒΦΑ4653Π4-ΨΙ9, ΥΠΠΟΑ 19/0582022, Α.Π.: 407854) and the consent of the Metropolis of Ioannina.

Felling dates as proxies for technological, economic and demographic dynamics in Bruges (c. 1200–1500 CE)

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The exceptional preservation of the cityscape in the medieval city of Bruges (Belgium) triggered dendrochronological research on numerous preserved roof constructions and floorings in historical buildings, that date from the Middle Ages up to the early modern period. Many of these construction timbers lack the preservation of wane edge. When timbers have partly preserved sapwood, the felling date can be estimated based upon known statistics on the expected number of sapwood rings. Usually, in larger timber constructions, multiple tree-ring series from the same building phase have partly preserved sapwood. Combining the sapwood statistics of individual tree-ring series into one model can provide a more precise and accurate estimate of the felling date, what can be demonstrated with the tree-ring dataset from Medieval Bruges. This methodology allows to synthesize the dating results of decades of tree-ring research on numerous buildings and to develop a typo-chronological framework of roof constructions. The Bruges tree-ring data set, for instance, shows that it took nearly two centuries before more advanced technological skill in the construction of roofs completely replaced the traditional common rafter roofs.

Furthermore, building upon the sapwood model for estimating felling dates, a method was developed to compute a summed probability distribution (SPD) for large data sets of felling date estimates. These summed probabilities allow to reconstruct temporal trends in building trade activity in an expanding medieval city, such as Bruges. When linked to the social status of the patrons of the building projects, it is observed that resilience to demographic crisis and political turmoil differs among the social groups and political elite of a medieval society.

The procedures for combining and summarizing felling date estimates is now available as a set of functions in the R-package ``fellingdateR``, and allows to standardize the reporting of felling date estimates and the analysis of (large) data sets of dated, historical tree-ring series.

Haneca, K., Debonne, V., Hoffsummer, P., 2020. The ups and downs of the building trade in a medieval city: Tree-ring data as proxies for economic, social and demographic dynamics in Bruges (c. 1200–1500). *Dendrochronologia* 64, 125773. <https://doi.org/10.1016/j.dendro.2020.125773>

The development version of the ``fellingdateR`` package can be installed and tested via:

<https://github.com/hanecakr/fellingdateR>

Seeing timber provenance through the exploitation of medieval and modern forests in the Mosan basin (Belgium): combined approaches of dendrotypology, growth disturbance and historical records

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This paper proposes to expose the potential of the Liège dendro-archaeological sources acquired since the 1980s to unravel the question of the provenance of original timber and forests exploitation in the Belgian Mosan basin between the 12th and 18th centuries. The forest provenance of archaeological wood is a long-standing and partly unresolved issue, especially on a local or small regional scale.

"Classical" dendro-provenance research often relies on growth patterns analysis between site chronologies and is often based on the comparison of chronologies of different length, composed of different volumes of individuals and mainly based on correlation coefficient (r of Pearson) / student t . However, this method reveals its limitations in terms of spatial resolution.

Several recent research-projects have made it possible to increase this spatial resolution while exploring new approaches (multi-agent analysis, DNA, isotopes, etc.) on current forests. The links between geographical origin, management modes (coppicing, CWS, HF) and exploitation practices (pollarding, trimming, belting etc.) paradoxically remain poorly or not explored. Historical sources, which sometimes indicate the location of forests and regulations on forestry uses or socio-economic status of owners and recipients, influence forest management methods and, by extension, their growth.

The proposal is to identify local signals, linked to ecological and anthropogenic origin, climatic signals, to characterize and locate them. The tools used here are dendrotypological analyses, disturbance analyses (growth releases) and pointer years. The studied corpus includes individual tree-ring series' dated from the 12th to the 18th century in the Mosan basin (Liège in particular) with comparison to Seine basin chronologies (FR). The analysis also includes written records (e.g. cutting plans from Liege chapters forests).

This study will also lead to questioning on the specialization of forest areas for the production of different types of timber or hybrid production between timber, joinery, fuel... The supply of timber for privileged buildings and on the scale of a watershed also leads to questions about socio-economic dimensions: did the large forest owners have recourse to the trade or could they supply themselves?

**Timbers from Late celtic, Roman and late Antiquity wells in SW-Germany:
Dendroarchaeology and implications for woodland management practices**

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Recent rescue excavations in the upper Rhine Valley on the western outskirts of Freiburg im Breisgau (SW-Germany) brought to light several wells whose timbers are dendrochronologically dated to the first and fifth century CE. Some of the timbers are exceptionally well preserved and show wood-working marks from the stem's felling, smoothing the surface and cutting the notches for the block construction. The combined analysis of tree ring width measurements and cross section dimensions showed that the block construction of one 39 CE-well (felling happened during late spring/early summer), in was made by using two reasonably large stems of oak. In another block construction from the 5th century CE besides oak planks, planks of *Populus* and *Alnus* were used. The presentation will compare these new features and tree ring data with other well timbers from late celtic and roman times from the region of SW-Germany and discuss implications for woodland management practices. Though such features pose technical difficulties to the excavation teams such as stability of the ground when digging in waterlogged unstable substrate, wells with waterlogged conditions are very important archives for wood working practices and archaeobotany due to the organic preservation and should be treated accordingly by archaeological services and agencies.

What can we learn from historical herbarium sheets? A preliminary dendrochronological study from the Arctic collections

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Studies about past climate conditions in the polar regions are limited to the length of instrumental data, which exceptionally reach beyond the 20th century. Using Arctic shrub chronology as a tool for climate reconstruction is limited by the age of tundra wooden plants, which rarely exceeds ~100 yrs. To overcome this main limitation, an innovative approach linking contemporary growing tundra species with growth-ring chronologies from specimens collected from historical botanical collections will be used. Research and discovery expeditions brought back collections of plants, animals, and minerals that added to the knowledge of the biotic environment of often newly discovered lands. These collections are now housed in museums and herbaria and are often forgotten and unavailable to visitors. Herbarium collections have been traditionally used for, e.g. systematics and taxonomy, studies of geographical distributions, and phenology observations. However, historical herbarium specimens have never been tested for dendrochronological research. Our studies have been conducted in the selected herbaria with the most valuable Arctic collections: Herbarium C in the Natural History Museum of Denmark, The Herbarium at the Royal Botanic Gardens Kew, the Cambridge University Herbarium and Oxford University Herbaria in UK.

We consider two elements of the initial selection of cards from a given herbarium, which we can refer to as “the time cluster” and “the area cluster”. It is important for the appropriate replication of the species of interest. Looking through the collections, we reviewed approximately 5,000 sheets with dry specimens in terms of indicating proper geographical location, date of collection, species, specimen size, and the curator's consent to sample collection. 25 sites useful for further dendrochronological studies were designated on the basis of metadata information and verified by historical sources. They are located in the following areas: Novaya Ziemlya, Kola Peninsula, Scandinavian Peninsula, Spitsbergen, Jan Mayen, Iceland, Greenland and the eastern part of the Canadian Arctic Archipelago. For detailed dendrochronological measurements seven dwarf-shrub species were selected: gray willow

(*Salix glauca* L.), polar willow (*Salix polaris* Wahlenb.), dwarf willow (*Salix herbacea* L.), net-leaved willow (*Salix reticulata* L.), arctic willow (*Salix arctica* Pall.), mountain avens (*Dryas octopetala* L.), dwarf birch (*Betula nana* L.). The youngest herbaria sheets dated back to the 1970s and 1980s, while the oldest went back to the early 19th century. On the basis of invasive sampling, approximately 400 samples were taken and analysed. Samples from the herbaria sheet can be sectioned with a GSL 1 sledge microtome into 15–20 µm cross-sections. In the case of poor quality wood, samples must be embedded in paraffin and then cut using e.g. Leica Rotary Microtome. Further preparation follows standard laboratory techniques and measurements. Preliminary results include: the creation of the first composite chronologies of historical specimens, a discussion of cross-dating parameters thresholds, shrub recruitment, past growth trends, and relationships with past climatic conditions.

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A Dendroarchaeology for Anatolian Bronze and Iron Ages - potentials and pitfalls

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This paper is a critical overview of our dendroarchaeological case-studies in Turkey within the framework of the Balkan-Aegean Dendrochronology Project: “Tree-Ring Research for the Study of SE-European and East Mediterranean Civilizations” with a discussion of existing challenges and prospects for the future. Tree-ring research and dendrochronology were formally introduced to archaeology of Turkey as early as the 1970s through Peter I. Kuniholm’s pioneering study on a 2750-year-old Iron Age tumulus housing a wooden burial chamber built of juniper logs with nearly 900 rings, the oldest known standing wooden structure in the world. This work together with his subsequent dating projects resulted in long regional tree-ring chronologies covering mostly the late antique and Ottoman periods in the wider Mediterranean region. The main goal of our project was to revive and build on this work through new collaborations, materials and perspectives in such a landscape full of huge archaeological potential offering a diverse set of data and questions on ancient societies. Another major goal was to extend such existing chronologies, identify problems, and fill in the gaps especially for the second and first millennia BCE, a time period that witnessed the rise and fall of many great polities in ancient Anatolia, such as the Hittites and the Phrygians, the emergence and disruption of long-distance trade networks, and a major crisis resulting in a new “house of cards”. Besides dating of a number of exceptional Late Bronze Age contexts, such as the 3500-year-old sacred spring of ancient Nerik, and identification of wood species and their origins, such as the Black pine timber posts used by the Early Bronze Age inhabitants of Seyitömer Höyük ca. 4700 years ago, we were able to identify issues arising from the quality, quantity, and management of available material. Our revisit to existing Anatolian tree-ring chronologies has revealed that sequences from Bronze and Iron Ages are still floating and represent only a small fraction of what has been unearthed thus far. During fieldwork we also observed a general loss of interest in dendrochronology among archaeologists, probably caused by the increasing popularity of other forms of absolute dating and long disappearances of dendrochronologists especially in less-favored areas. Our ultimate goal is to restore and foster the role of dendroarchaeology in shaping and answering questions on human past and

environment while outlining prospects for the future in collaboration with local researchers in a geography offering many great challenges but full of surprises.

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Dendrochronological database as an indicator of historical wood utilization and building activity in the Czech lands over the period 1400–1900

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Large dendrochronological databases may provide information about development of settlement and building activity which is the result of socioeconomic, political and demographic changes in the past. In this study, we use 8'135 precisely dated timber constructions from a dendrochronological database to investigate temporal changes in wood utilization and building activity across the Czech lands from the 15th to the 19th century. Our results suggest that the species selection was based on wood properties and stem geometry. Most of historical constructions represented mainly by roofs, ceilings and log walls, are made of fir and spruce. Oak wood prevail in belfry constructions. Although fir prevailed in timber construction in the late- Medieval and post-Medieval times, planting of spruce monocultures resulted in its significantly increased utilization by the end of the 19th century. Comparing felling dates with historical events demonstrated that building activity was negatively associated with intense wars, particularly during the Thirty Years' War (1618–1648). After the Peace of Westphalia (1648), socioeconomic renewal and demographic growth were reflected in an upsurge of building activity, especially ecclesiastical buildings. While the construction of ecclesiastical and noble buildings culminated around the 1720s, rural buildings peaked in the 1780s and the 1820s. Higher number of felling dates were detected when strong and/or frequent windstorms occurred. This study demonstrates the value of dendrochronological databases as an indicator of historical wood utilization and provide understanding of building activity in Central Europe.

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Monitoring wood phenology with band dendrometers: opportunities and pitfalls

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Wood formation phenology is pivotal in understanding the development, functioning and adaptation of trees to environmental factors. This information can provide insights about the impacts of changing environment on tree growth and productivity. Numerous studies have investigated the effect of climate on the onset, cessation, and duration of the growing season over the last decades. Many studies use stem microcores for direct observation of xylogenesis and are labor intensive, therefore many other studies utilize indirect observations from dendrometers. However, it has not been properly assessed yet if dendrometer studies can provide reliable estimates of wood formation phenology.

To verify the possibility of describing the phenology of wood formation using dendrometers, we compared critical dates estimated with band dendrometers with those from xylogenesis monitoring. We collected data from band dendrometers and xylogenesis for five tree species exhibiting contrasting tree-ring structures (i.e. softwood vs hardwood, diffuse vs ring porous), bark types (i.e. smooth vs scaled vs fissured) and leaf habits (i.e. evergreen vs. deciduous, needles vs. leaves), contrasting sites (warm vs cold) and years (humid vs dry).

Weekly stem circumference variations and microcores were collected for three or more years, on the same trees for six different tree species (European beech, European larch, Norway spruce, Scots pine, silver fir, and pedunculate oak) growing in five different sites located in Eastern France. Band dendrometers measurements were fitted using classical growth curves (5-parameter logistic curves) to provide the days of the year for which 5 % (DOY.05) and 95 % (DOY.95) of the annual growth is completed. The xylogenesis monitoring provided near-direct observations of five critical dates of wood formation: the onset of cell enlargement (bE), the onset of cell wall thickening (bW), the apparition of the first mature cells (bM), the cessation of cell enlargement (cE), and the cessation of cell wall thickening (cW). The relationships between the critical dates provided by the dendrometers and those provided by the microcores were explored using linear mixed effect models.

The average goodness-of-fit of the growth curves was high for the six species ($R^2 > 0.90$), however larch and pine showed higher individual variations. Significant correlations were found between total growth from the growth curves and the total number of cells produced from xylogenesis observations for all species, except for oak.

Concerning the onset of the growing season, the critical dates from the two approaches exhibited significant correlations when comparing DOY.05 and bE for beech, silver fir, spruce, pine, and larch, but not for oak. On the other hand, for the cessation of the growing season, cE and DOY.95 only show significant correlation for beech and oak, while no significant correlation was observed for larch, spruce, silver fir, and pine.

In larch, the mean of bE is increasing with growing elevation. This is also true for mean of DOY.05. Although no significant correlation between the two approaches, their relationship with growing elevation is maintained.

When the correlation between bE and DOY.05 is grouped by year in beech, the correlation is only significant for the years 2017 and 2018, despite the slope of the regression lines remaining relatively constant.

When grouped by bark type, smooth bark (beech) and scaly bark (silver fir & spruce) species had significantly higher mean R^2 than fissured bark (larch, oak, and pine).

The information provided by band dendrometers highly depends on the characteristics of the studied species. In the case of species presenting smooth bark and 'homogeneous' tree-ring structure, band dendrometers allow to estimate the onset and the end of wood growth. On the other hand, for species presenting rough bark and 'heterogeneous' tree-ring structure, band dendrometers do not allow to estimate wood growth characteristics.

This means that, in general, band dendrometers can't be used to describe wood formation phenology without any prior xylogenesis study. However, our study also shows, that for some very important species (i.e. beech), band dendrometers can provide a simple and convenient tool to approximate wood formation phenology.

dd+ - A new dendro software for large data sets and for institutions with archives

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Most dendro software packages lack features that are of great importance to long-standing dendro-institutions with large numbers of samples in their archives and with numerous datasets on their hard drives. Among these essential features are (i) context information and metadata for each sample and measurement, (ii) detailed information on the structure and content of every mean curve, (iii) data consistency, (iv) the definition of subsamples as dynamic or static, (v) ability to crossdate using thousands of measurements, (vi) provide output tables for external use such as GIS-systems, (vii) defining roles and rights for different users, (viii) provide flexible vector graphic export options; and several others.

The new software dd+ covers all these issues. However, it is not meant as an all-in-one software for dendro studies. Many numeric analyses are better done in R. It rather aims at providing stability, transparency and consistency for large datasets together with high performance crossdating tools.

dd+ is a Microsoft server SQL database with in-built dendro features. A SQL query-builder allows to define subsets and groups based on a wealth of attributes. These groups can be saved either as dynamic or static list and form the base for browser based management, editing, correlation or the production of database-tables for external use such as GIS. There are two browsers for wood samples and two for mean curves, all of which can be used independently by applying SQL queries or manually picking samples and mean curves.

Calculation procedures are optimised for large datasets. Crossdating 851 vs 1204 series in all possible synchronous positions takes less than 3 min. Crossdating is assisted by direct visual presentation of individual pairs which can be set to visible or hidden. dd+ enforces data consistency by checking your crossdating decisions. Mean curve construction and dating is only possible if all single crossdating positions are consistent.

By now, dd+ uses the Heidelberg-format and excel-files for import and export. Knowing about the weaknesses of these formats, they seem helpful for overcoming the many problems of backward-digitalisation. Once data are entered, the data model opens new

possibilities. Future development aims at a xml format for data exchange. The latest version 2.6 covers an csv-export in long format for import into R. Meanwhile, the standardisation of meta data aids in the exchange between labs.

Taking part: dd+ is not open source, but it aims at an open data policy and common data standards. It has been programmed by professionals in cooperation with the Zurich lab. It comes without licensing fees, but it is not free of costs: Whoever wants to use dd+, joins the user community "ArGe dd+" by a contract. All users share the costs of support by a fixed amount per year. The community decides by simple majority on further development and improvement projects and the costs are shared. For the moment, dd+ has a focus on managing samples from historical and archaeological contexts. Future versions will add ecological aspects.

If you are interested in dd+, please contact niels.bleicher@zuerich.ch.

Combining scientific methods for origin verification of timber: does accuracy increase when wood chemistry and genetics are integrated?

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Illegality in the timber trade harms people, ecosystems, and local economies and hinders sustainable initiatives, particularly in tropical regions. One of the main forms of fraud is false declaration of origin. To aid law enforcement and verify timber origin, various scientific methods are under development, including chemical methods such as multielement analysis and stable isotope ratios, as well as genetic methods based on SNPs. These methods all rely on natural variation across a species range, but the processes causing the geographic variation differ for each method. Combining their individual strengths may achieve the highest tracing accuracy. However, this has never been tested and currently, these methods seem to compete with each other to be regarded as 'best practice'.

To test the combined performance of multi-element analysis, stable isotope ratios and genetic SNP analysis for tracing timber origin, we established an extensive geolocated reference dataset as part of the TIMTRACE project. The dataset includes samples of an important African timber species, *Azobe (Lophira alata, Ochnaceae)*, from 15 sites across Cameroon, Gabon and Congo. We applied classification models to identify timber origin based on the individual methods, as well as a combined model. We also developed origin prediction maps using Quantile Regression Forests, which allow for a comparison of accuracy (correct origin identification) as well as precision (the area of predicted origin in km²).

The results showed varying tracing success for each method. Multielement analysis was effective at identifying chemical clusters that were 50-800 km apart, with high accuracy. Stable isotope ratios did not show clear geographical patterns in our study area under 500 km and assignment accuracy was low. The genetic analysis had potential to identify different sites within and between countries (50-800 km) with high accuracy. The combined classification model showed increased accuracy and precision for specific locations, but other sites were already well-classified by either multielement or genetic analysis alone. The most suitable method for tracing will depend on the provenancing question at hand.

Back to the wood: Cross-dating difficulties of *Betula pendula* tree-rings from the Spanish Pyrenees. When establishing the chronologies of the rings becomes a complex and laborious process

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The aim of this study was to establish and analyse the chronologies of birch rings (*Betula pendula* Ehrh.) from five localities located in the central Pyrenees of Catalonia, NE Spain at an altitude between 1,433 and 2,049 m asl.

The sample sites were selected along a 24 km transect from east to west. Three sites were located in Valls d'Àneu (42°N, 1°E) and the other two in Aigüestortes (42°N, 0°E). We sampled 68 trees and the number of cores extracted was 176.

Cores preparation was done following standard dendrochronological techniques. To identify the tree-rings, we polish the cores with successively finer grit sandpaper, up to 14 microns.

Tree-ring cross dating was quite complex. Tree-ring boundaries were not always well defined. To solve the problem, we used two techniques. We first scanned the samples and inverted the colour of the images. In this way, the boundaries were better highlighted. Then we cross-date each sample with another core from the same tree. Comparing the two samples side by side helped us to be sure if what we were seeing was one ring or two, or if it was a missing ring.

The birch trees studied showed a huge intrannual variability in the tree-ring widths. On the same core there are rings that are over 1 cm thick and rings that are barely over half a mm. In young trees we found very large rings of more than half a centimetre, while old trees had many rings of less than 1 mm. Wedge rings are quite frequent and might become a missing ring in the core of the opposite tree radius. Missing rings were also quite frequent. This high plasticity in trees growth means that small changes in the environmental conditions where a tree grows are reflected in the ring sizes. In addition, therefore, despite the fact that the different localities are relatively close, we found large differences between the thicknesses of the rings of the different trees, which makes it difficult to cross-date the sequences of tree-rings between sites.

The sampled trees were quite young. The vast majority of the trees were between 30 and 50 years old. Although, trees up to 96 years old were also found. The exploitation of

birches for firewood that was done until the end of the 1980s is the main cause of the lack of old trees in this area.

COFECHA mean series intercorrelation was improved by (1) removing those series with many flags, some of them were impossible to cross-date, (2) deleting the initial sequence of rings. Finally, we got higher r-values, up to 0.542 ± 0.073 . Mean sensitivity was high, $MSx = 0.404 \pm 0.099$, a good indicator of the plasticity of birches. MSx for pines in nearby places ranges from 0.1 to 0.25.

In the locality of Arroze, where pines and birches compete, we had great difficulties to get reliable cross dating, and we only could select 74% (70%) of the cores (trees). From the more mesic sites as CJou we could select 96% of all cores, which represent 100% of all trees. In the localities of Llong and Lebreta we selected 90% of the cores and 86% of the trees. In the last locality, CC, we managed to use 80% of the cores of 78% of the sampled trees.

Radiocarbon dating single tree-rings for annual precision records of environmental change.

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Radiocarbon dating is a powerful tool to date organic material back to c. 50,000 years ago. This is made possible through the radiocarbon calibration curve which calibrates radiocarbon estimates to the calendar scale. The curve is built by carbon dating samples with a known calendar age, for example, tree-ring dated wood. In the past, due to the need for large samples, such wood was cut into 10-ring blocks and so the accuracy of the curve was limited by the available data. As technology improves, we are now able to date samples as small as single tree-ring widths. New data of this sort has already had significant implications in radiocarbon calibration through the discovery of so-called 'Miyake events', that is, previously unobserved spikes in atmospheric carbon-14 levels in the space of 1-2 years.

My research project focuses on radiocarbon dating significant numbers of new single-year tree-rings. If inputted into the radiocarbon calibration curve, this will increase the curve's accuracy, and thus not only improve our precision of dating specimens but could have a considerable impact on our ability to understand previous climate activity, for example through accompanying measurements of stable isotopes.

Previous data collection has shown high variability within the radiocarbon dates that form certain areas of the internationally agreed radiocarbon calibration curve. Sometimes this variation appears large, but with little bias. Other times there appears to be an offset between datasets taken from different geographical areas or sampled in different labs. These offsets, particularly in the Northern Hemisphere, are little understood, and unaccounted for by independent laboratory errors. Instead, it is suspected that they have latitudinal or altitudinal dependences, and so have the potential to contain valuable climatic information. Further clarity on the matter could have significant repercussions, not only in palaeoecology, but in radiocarbon calibration as this could also affect how multiple carbon estimates should be calibrated.

Currently, no consecutive single-year data surrounding 8000 cal yr BP has been included in the radiocarbon calibration curve. This section of the curve is supported by particularly little data, and the data that does exist there shows potential offsetting between Seattle, Belfast and Heidelberg radiocarbon dated tree-rings. Here we present radiocarbon estimates from Scots Pine found in Sluggan Bog, Northern Ireland, dating back to c.8000 cal yr BP, in an aim to try and clarify this. This time period covers the important 8.2ka event (Torbenesen et al. 2015), a period of sudden cooling in global temperatures which occurred c. 8200 cal yr BP.

Detrending tree rings in closed-canopy forests for climate and disturbance history reconstructions

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Canopy disturbance events in forests often increase light availability and growth rates for surviving trees. Release-detection methods based on tree-ring patterns reconstruct forest disturbance histories by identifying the initiation of rapid growth associated with these events. Conversely, dendroclimate reconstructions minimize these rapid growth responses by detrending entire ring-width time series to resolve underlying climate signals. Incorporating advantages from both of these approaches, we present a new disturbance-detrending approach for identifying and isolating canopy disturbance time series in ring width using a combination of radial-growth averaging and dendroclimatic detrending methods. Using examples from deciduous and evergreen species in forest regions across eastern North America, we use radial-growth averaging to detect release events and then power transformation and age-dependent smoothing splines to detrend individual release events, separating a tree's growth response to canopy disturbance from climate. The resulting canopy disturbance time series agree with documented forest histories from each forest site. Removing this canopy disturbance time series from the ring-width series enables a climate reconstruction that correlates with monthly values of temperature and precipitation. These correlations are often higher than found with traditional detrending methods including negative exponential curves or two-thirds spline. This method provides an alternative approach for detrending disturbance events in closed-canopy forests that should be accessible and useful for both ecological and climatological reconstructions using tree-ring widths. This method may also have applicability for detrending artifacts in blue-intensity time series of past climate, such as the heartwood-sapwood transition.

Recording and measuring cambial activity and xylogenesis using XyloJ, a dedicated plugin for ImageJ/FIJI

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For the last two decades, the study of xylogenesis has become one of the main methods to understand the responses of forest ecosystems to environmental changes, with studies from individual trees to global level, and an important contribution to understand carbon sequestration models. In general, these investigations are based on the observation of xylem and phloem formation phases on microscopic sections, with several features that can be recognized or quantitatively measured. For this, data are usually retrieved from digital images, with many laboratories using different methods.

We recently developed XyloJ, a plugin specifically aimed at recording stages of cambial activity and xylogenesis, as well as performing measurements of regions of interest on microscopic images. XyloJ was completely written in Java, and runs in ImageJ/FIJI, an open image analysis tool widely used in many scientific fields. ImageJ runs on any platform (Windows, iOS, Linux), it is very efficient at manipulating many image formats, and can be easily extended with numerous plugins. As XyloJ is completely integrated within ImageJ, it can be combined with many other functions and plugins, extending its functionality.

In this work, we show the main features of XyloJ, and how to use the plugin for the study of xylogenesis. This includes how to manage and open image files, and the recording of different phases identified, cell countings, and measurements of growth zones. Finally, we explain the way data are stored, and how they can be exported for further processing.

Open-Source Solutions for High-Resolution Spectral Analysis of wood using CaptuRING

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Technical innovation and scientific discoveries are continuously evolving due to reciprocal positive feedback. In the last two decades, computing capacity and digitization tools have undergone a fast development, with cutting-edge tools for research becoming increasingly affordable. Moreover, the emergence of the open-source philosophy has created a programmer community devoted to customizing solutions that are freely available to any researcher. Notwithstanding, these community-built solutions must enforce accuracy and repeatability to ensure their reliability for scientific research.

Open solutions with high reliability and precision are emerging as a valuable instrument to dendrochronological techniques. Furthermore, these open tools are not limited to software, and they can be used in a wide range of applications thanks to the development of Arduino-based systems and the generalization of 3D printing. These open-source advances increase our capacity to collect and analyze dendrochronological samples and open a new room to promote this area in developing countries.

Thus, open-source tools have reached the field of dendrochronology, developing specific software and hardware for image analysis. Lack of color homogeneity and flatness of wood samples hampered sample digitization in the field. However, the recently available open tools have promoted dendrochronology in terms of spatial resolution capacity, reaching impressive results.

Wood microdensitometry shows a high potential to evaluate climate responses in wood and to detect different events. Blue intensity of wood samples, especially conifers, shows a high correlation with densitometric values. This makes blue intensity proxy a low-cost alternative to densitometry, since the relatively high equipment costs, time-consuming preparation and measuring procedures required for X-ray densitometry can be avoided. Nevertheless, there are still open questions about the origin of the variance in the blue channel of wood cells and its consistency.

Here, we present a new development of the open-source tool CaptuRING for digitizing wood cores in high resolution (>5 800 dpi/0.004 mm of pixel size) to be used for densitometry studies with standardized blue intensity values.

In this research, we studied the spectral reflectance of different woods. We digitized wood cores from three conifers (*Pinus sylvestris*, *P. nigra*, *P. pinaster*, and *P. halepensis*) using three different long-pass filters which restricts visible spectrum up to three wavelengths (440, 480 and 540 nm). We captured individual images at each core with the appropriate filter using a color scale to evaluate the reflectance spectrum of wood from Ultraviolet to 440, 480 and 540 nm. We then compared the blue intensity values at the different captions with the results of X-ray microdensitometry for each core and analyzed the homogeneity of the blue intensity proxy at high resolution (>4800 dpi).

The development of the CaptuRING tool with spectral resolution has opened up new possibilities to analyze proxies as a function of wood reflectance at a much higher resolution than the current alternatives in digitization. Furthermore, there is great potential for further improvements for the benefit of the research community through the use of open-source tools.

Using dendroprovenance to trace the origin of instream wood at the watershed scale

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Instream large wood (LW) is a critical element in understanding river ecosystems, and research in this area has been growing in recent years. Its presence can increase the geomorphic and ecological diversity of the ecosystem, but also pose a risk to infrastructure and population during flood events. Understanding the origin and dynamics of LW can help managers to optimize river and riparian forest management and reduce the associated risk. To this end, in this project, we used dendroprovenance methods to develop a fingerprinting technique for determining the origin of LW in mid-sized river basins.

We study a 50 km reach of the Rhone River between the city of Geneva and the Génissiat Dam in France. This reservoir retains all of the woody material supplied by the two main tributaries of the reach: The Arve River (coming from the Alps Mountains) and the Valserine River (from the Jura Mountains). In order to determine the origin of the LW that flows into the dam, our goal is to distinguish source areas between and along these two sub-catchments.

For this purpose, we have explored several sources of information:

1. The Deuterium and Oxygen-18 stable isotopes in the cellulose: these isotopes from the water molecule present a spatial variation due to the fractionation that occurs during evaporation-precipitation processes. The tree absorbs this isotopic signal and stores it in the cellulose. Then, reference samples and unknown origin samples can be analyzed with a mass spectrometer to infer the source areas of LW. To assess whether the isotopic signal does not change when the wood is in the water, we are conducting an experiment in a small river with anchored logs, which we sample every four months.
2. The chemical composition of wood cellulose: it provides information about the area's geology and what nutrients were available where the tree grew. We have used inductively coupled plasma optical emission spectrometry (ICP-OES) or X-ray fluorescence spectrometry (XRF) to analyze de samples.
3. The riparian vegetation composition and spatial distribution: we have collected data from the riparian area (e.g., tree species, forest density, dead wood present in the floodplain, lateral connectivity with the river, etc.) that give us information about which areas are more or

less likely to provide certain types of wood (size and species). This, together with hydrological data, provides useful information about the wood that will reach the dam.

By combining all these approaches, it may be possible to distinguish between different source areas of LW within the catchment of this reach of the Rhone River, and to understand better the factors that influence the supply of LW to the river system. We aim to develop a method that can be applied to similarly scaled mountainous catchments to determine the origin of instream large wood.

Using RCS and Signal Free RCS to preserve low frequency trends in tree-ring width and density chronologies

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Paleoclimatic research using tree-ring derived data faces the challenge of selecting the appropriate detrending method to retain low frequency signals in climate reconstructions. Issues of signal preservation can be of biological or statistical origin but there are multiple methods addressing these, among them regional curve standardisation (RCS) and signal-free (SF) RCS, which are increasingly used to preserve the potentially full spectrum of variance in tree-ring data. Here we use multi-centennial composite and shorter living-tree datasets of both maximum latewood density (MXD) and tree-ring width (TRW) from Scandinavia to evaluate differences between RCS and SF RCS detrending. A similar approach is used for data from the European Alps to investigate differences in a more rapidly warming environment. We demonstrate that the detrending method has a larger impact on TRW than MXD and that both methods should not be used on living-tree datasets.

QWA goes AI: towards a deep learning based version of ROXAS

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Quantitative wood anatomy (QWA) has proven to be a powerful method for extracting relevant environmental information from tree-rings. However, the QWA approach is methodologically challenging and time-consuming, with measurements from anatomical images using tools such as ROXAS being one of the bottlenecks. In recent years, deep learning has drastically improved the performance of most computer vision tasks. We are therefore working on a revised version of ROXAS based on deep learning techniques to improve and facilitate the cell-detection process. Here, we present first results from evaluating the performance of three possible deep learning approaches: semantic segmentation, instance segmentation, and panoptic segmentation.

To train the deep learning methods we compile an extensive dataset of anatomical images from conifers with a wide variety of species, locations, magnifications, processing protocols, and image qualities. We manually label cell outlines and take care to correctly handle common artifacts such as broken cell walls and wrongly detected cells (pit chambers, ray cells, resin duct cells). We use a subset of this dataset to train one representative deep convolutional neural network for each type of segmentation. The unseen remainder of the dataset is used for evaluation. In addition, we applied the best deep learning segmentation model to an existing high-quality QWA chronology dataset from Northern Finland (Björklund et al. 2020) to compare the summer temperature reconstruction skills of deep learning and traditional ROXAS.

Our results show improved performance for the deep learning model compared to automatic ROXAS output. Based on the computer vision metrics “Panoptic Quality” deep learning outperforms automatic ROXAS by 0.864 versus 0.773. This results in a percentage error reduction of 57.8% for lumen area, 63.2% for cell wall thickness, and 54.1% for cell count compared to automatic ROXAS. In addition, our deep learning model provides high-quality results even for lower-quality images where the automatic ROXAS detection yields insufficient results. The downstream consequences of these improvements for the Northern Finland dataset are partly masked because of high replication in the QWA-based average chronologies. Yet, the inter-series correlation (r_{bar}) using the deep learning model was consistently higher

than automatic ROXAS, and higher or similar when using ROXAS output that was additionally improved through time-consuming manual editing. The corresponding correlation with warm-season (April-September) temperatures followed the same pattern, i.e. the deep learning output was as good, or even better than the manually edited ROXAS output, notably without human operation time for cell editing. Our research demonstrates the potential of deep learning for higher-quality segmentation with less manual post-processing time, saving weeks to months of tedious work per dataset used in a dendroclimatic context without compromising data quality. This will significantly increase the efficiency of the anticipated ROXAS AI compared to the current ROXAS version.

A Python package implementing Direct Reconstruction Technique (DIRECT) for dendroclimatological studies.

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Direct REConstruction Technique (DIRECT) is a dendroclimatological method that constructs a climatic response surface to simultaneously account for changes of tree-ring parameters and tree age to use it for climatic reconstructions. Unlike classical standardization methods such as Traditional Standardization (TS), Regional Curve Standardization (RCS), and their signal-free (SF) modifications, DIRECT unites the processes of standardization and construction of a transfer function. This takes into account the nonlinear climatic responses of younger and older trees. Here we describe an open-source Python package that implements DIRECT. This package provides functionality for climate reconstruction and the estimation of different types of uncertainties based on bootstrapping. It also includes supplementary functions for estimating the most optimal combinations of parameters of the method. Various visualization options allow the researcher to investigate proxy-climate relationships. We provide examples illustrating the use of this package for the reconstructions of summer temperature based on maximum latewood density data from the Northern Fennoscandia and blue intensity data from the Caucasus. We also compare the reconstructions based on DIRECT with ones based on RCS and TS-SF standardization methods. Now the broad community of dendrochronologists can apply this methodology using open-source Python code.

Using bias analyses to improve tree-ring ecological data

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Today, ecological data, including tree-ring data is abundant and easily accessible across scales. However, most of it the available data has been collected haphazardly by decades of voluntary contributions. As a consequence, ecological big databases tend to be unrepresentative and unbalanced, which questions the ecological inferences we make from them. However, we can use representativity analysis and existing environmental data to guide the new acquisition and relevance of new tree ring data. We use data from the International Tree Ring Data Bank and other large long-term tree growth data across Europe to how highly targeted sampling guided by representativity analyses can help pushing existing big tree-ring data towards being more ecologically representative and explore how this affect ecological analyses and conclusions. We will discuss the implications for past and future tree ring work and the challenges ahead to make dendroecological data more useful and applicable to real world ecological studies.

National-wide Bayesian fusion of tree-ring and National Forest Inventory data in South-Western Europe

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Unbiased estimations of carbon stocks and fluxes in forests under future climatic change require accurate and robust process-based vegetation and ecosystem models to be able to account for changes in climate as well as forest structure and growth. These models have been developed using short-term observations such as manipulative experiments, and satellite and eddy-covariance data hardly exceeding 30 years. As a result, they are relatively skillful at reproducing short-term observations of transpiration, biomass growth and forest carbon balance but their century-long responses and projections diverge greatly. Several longer empirical data sources such as tree rings and National Forest Inventories (NFIs) have been used to benchmark the simulations of those process-based models at longer time scales. However, the lack of annual resolution in field tree remeasurements (NFIs) and the lack of quantitative estimates of forest biomass stocks from individual tree cores (tree rings) limits the conclusions that can be drawn from those model-data comparisons. Combining or fusing the tree-rings and dendrometric NFI data, would allow the strengths of both data types to inform reliable and annually resolved forest carbon storage estimates. In this work, we aimed at fusing data from the Spanish NFI with tree-ring data from the dominant trees of permanent NFI plots. We focus on *Fagus sylvatica* L. as the target species over the last three inventories (1986 – 1996; 1997 – 2007; 2008 to date) and selected NFI plots with target species dominance larger or equal to 80 %. In total, 205 NFI plots and cores (i.e., one core per plot) composed the database of *F. sylvatica*. We calculated stand variables from the NFI (e.g., basal area, stand density indices), site index from literature and derived climatic variables at monthly resolution from ERA5 data set. Then, we fused tree ring growth data and tree diameter at breast height using a Bayesian state-space model (see Heilman et al 2022, DOI 10.1111/gcb.16038 for *Pinus ponderosa*) where the “true” diameter increment is a latent variable and, in fact, the variable of interest. As predictors, we included covariates operating at tree size, stand-scales properties and climatic scales. Our results further demonstrate that fusing tree-ring and NFI data is a reliable tool that can be applied to generate annually-resolved tree-level diameter estimates and

forest-level carbon stock estimates. The model validation plots (that is predicted vs observed tree diameter increment) suggested a good model fit. We found a negative effect of stand competition and a negative effect of warm and dry summer conditions on tree growth. Furthermore, high temperatures at the end of the winter enhanced *F. sylvatica* growth. Additionally, this methodology could be expanded to other tree species and biomes allowing regional to the global assessment of the evolution of forests as carbon stocks under forecasted changes in climate.

Assessment of arctic warming impact on Siberian hydrology using online tool TRISH: Tree-Ring Integrated System for Hydrology

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Accelerating warming in the Arctic and loss of sea-ice cover unfolding over the last 25 years raise many questions about the feedbacks of terrestrial systems coupled with the Arctic system. Freshwater originating in the largest Arctic watersheds may stimulate Arctic warming via increased volume and changed seasonality of river flow. Growing societal awareness of knowledge gaps about interactions among Arctic teleconnections calls for new climate-hydrology networks and predictive tools across the Arctic-dependent regions. To advance our understanding of the contribution of regional hydrology behavior to the Arctic warming, we explored hydrological potential of tree-ring networks across the Yenisei River Basin, the second largest Arctic river. The Yenisei River is 3,487 km long, drains 2,580,000 km² area from Mongolia throughout Middle Siberia to the Kara Sea, and accounts for 1.5% of global freshwater runoff.

Four reconstruction models for the Yenisei River flow are built with tree-ring width networks from the upper and lower reaches of the basin. Two tree-ring networks used include larch (*Larix sibirica*) sensitive to summer temperatures well as larch with a coupled climatic signal for fall-winter precipitation and temperature in spring to early summer. Models for the upper reach rely on monthly observed discharge at the Kyzyl gauge (1,025 m³ s⁻¹ annual average, 115,000 km² drainage area); this reach represents primarily pristine drainages of the Yenisei watershed across the Sayan Mountains in Tuva. The models explain 52% of winter Nov-Apr and 26% of annual Oct-Sept discharge. Two other tree-ring models from the lower reaches use naturalized monthly discharge simulated with the University of New Hampshire Water Balance Model (UNH-WBM) using the ERA5 reanalysis product for temperature and precipitation inputs near the Igaraka gauge (15,517 m³ s⁻¹ annual average, 2,440,000 km² drainage area). The simulated discharge adjusts for anthropologic impacts on river flow distorted by large hydropower cascades and industrial water net withdrawals at the lower reaches. The lower-reach models explain 50% of winter (Nov-Apr) and 36% of annual (Oct-Sept) discharge at Igarka, which is the northernmost ocean-tide-free hydrograph on this river system and is only 250 km south of the estuary of the Yenisei River. The multi-decadal

variability of the reconstructed seasonal discharge varies considerably across the basin for the last 300 years.

The tree-ring modeling of Yenisei River discharge uncovers large seasonal changes in flow likely related to thaw of permafrost in the south due to forest fires and climatic warming. Winter discharge has a dramatic 80% upsurge over the last 25 years in the south, and increased variance but no significant decadal trend in the north. The annual discharge of the Yenisei River across its vast basin changes coherently: high flow in the 1970s-1980s and two prominent intervals of the low flow around 1940s and 1740s. The recent increase in reconstructed Yenisei annual flow is higher than the long-term reconstructed mean and the observed historical flows but this trend has weakened as flows decreased in the most recent decade.

The reconstruction modeling was done with a new online tool – TRISH, or Tree-Ring Integrated System for Hydrology. This is a tool for analyzing tree-ring data in a spatial framework via the EarthAtlas Map Server, Map Data Calculator and UNH-WBM. The tool enables access, display, analysis and visualization of hydroclimatic signals in tree-ring networks using historical observations and reanalysis products. We discuss 1) the contribution of historical networks of temperature- and moisture-sensitive tree rings to hydrological modeling in Arctic watersheds, and 2) challenges in linking surrogates simulated by water balance models to tree-ring data.

Generalization capability of deep learning based automatic tree-ring detection and measurement

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Manual measurements of annual growth rings in trees are slow, labor-intensive and subject to human bias, hindering the generation of big datasets. We developed an alternative, a neural network-based implementation that automates the detection and measurement of tree-ring boundaries. We iteratively trained our Mask R-CNN on over 8,000 manually annotated rings. The CNN performed well, recognizing over 98% of ring boundaries (precision) and a recall value of 96% when tested on real-world imaged Norway Spruce cores. Additionally, we have implemented automatic measurements based on the minimum distance between rings. With minimal editing for missed ring detections, these measurements were a 98% match with human measurements of the same samples.

We present here results reflecting how a spruce-trained CNN can generalize to other species. We tested its performance on a set of coniferous and angiosperm species as well as images from various sources. The model demonstrates good generalization to other conifer and some broadleaf species even when their resolution drops much lower than the resolution of the training images. Our CNN is readily deployable through a Docker container and requires only basic command line skills. Application outputs include editable annotations which facilitate the efficient generation of ring-width measurements from tree-ring samples.

Exploring non-linearity in Norway Spruce dendroclimatic models in Eastern Carpathians (Romania)

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Decrypting and understanding tree growth response to climate is still a central challenge in tree ring science. Various statistical methods were applied, from linear correlation to machine learning techniques, from frequentist to bayesian approaches or process-based models. The study aimed to evaluate the relationship between tree ring index and seasonal climate parameters (temperature, precipitation and SPEI) using machine learning techniques (Random Forest Analysis - RFA) and a non-linear method (generalized additive mixed model - GAMM). The dataset consists of a large tree-ring network of 156 Norway spruce chronologies (2994 trees), from managed stands, covering different age classes and distributed along an altitudinal gradient in Eastern Carpathians (Romania). Daily climate data from E-OBS grid data downscale to a high-resolution grid (1 km²) (Moreno and Hasenauer (2016) were aggregated on a seasonal time scale. Raw tree ring widths were detrended using a 30-year cubic spline with a 50% frequency cut-off. Based on Random Forest analysis, the most important climate variables on Norway spruce radial growth were the drought intensity from the previous autumn and summer. The winter temperature had high relative importance as well (RFA). The differences in growth-climate responses within the altitudinal classes were highlighted. Partial dependence plots from RFA indicate a non-linear relationship between spruce growth and previous autumn temperature as well as the SPEI and the previous summer SPEI. GAMM models reveal a positive linear correlation of the growth index with summer temperature and a negative correlation with previous summer temperature. We can observe a non-linear relationship between growth and previous autumn temperature with previous summer precipitation, respectively. Our preliminary results show that the relationship between Norway Spruce radial growth and climate, in the Eastern Carpathians, is complex and requires future investigations.

Multi-proxy crossdating for chronology improvement

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Here, we present a multi-proxy crossdating approach, including tree-ring width (TRW), maximum latewood density (MXD), stable carbon ($\delta^{13}\text{C}$) and radiocarbon (^{14}C) isotope measurements to overcome tentative relict wood dating in an early period of the Mt. Smolikas chronology (Greece). Initially developed from 878 TRW and 192 MXD series of living and relict Bosnian pines (*Pinus heldreichii*), the record became the longest high-elevation tree-ring chronology from the Mediterranean, and was used to reconstruct hydroclimate and temperature variability back to the 8th century CE. New annually resolved and non-pooled $\delta^{13}\text{C}$ measurements, however, now reveal initial dating errors of some TRW series in the first millennium. Re-dating of the oldest samples shifts the start of the Mt. Smolikas chronology from 575 back to 468 CE. The new dating is corroborated by wiggle-matching of annual ^{14}C data from the same trees along the 774/775 CE radiocarbon spike. Our study demonstrates the importance of independent age validation for chronology development and outlines how multi-proxy crossdating can enhance dating success in periods of low sample replication.

Delineating forest vulnerability to drought using a process-based growth model

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Stress due to recurrent droughts has become a very important driver of forest growth worldwide. The evaluation of tree growth patterns and their response to climatic variables is essential to determine the capacity of forests to face climate extremes such as droughts. Drought often causes growth decline and forest dieback. This is the case of some silver fir (*Abies alba*) populations in the Pyrenees, southwestern Europe that show ongoing dieback since, at least, the 1980s. We analyzed 21 silver fir stands with different intensities of dieback, assessed as the percentage of crown defoliation and tree mortality, we quantified their growth patterns and trends, and we characterized their responses to climate variables (maximum and minimum temperatures, precipitation and water balance). Then we assessed how growth deviated from climate baseline using the process-based Vaganov-Shashkin growth model, which explicitly considers non-linear climate-growth relationships. To do this, we calibrated all sites in a period (1970-2000) prior to the recent increase in drought severity and analyzed the residuals of the verification period (2001-2020). The common growth patterns among the 21 tree-ring width site chronologies allowed grouping them into: two western clusters (west A cluster with low dieback incidence vs. west B cluster dieback incidence) and eastern and central clusters. The forests showing most intense dieback, i.e. highest defoliation levels, were mainly located in low-elevation sites of the western Spanish Pyrenees (west B cluster). Trees in these stands displayed the lowest growth rates and the highest year-to-year variability in growth and their growth was limited by late-summer drought stress, specifically high water evaporative demand. These sites also showed stronger climate-growth correlations compared

with central and eastern clusters. Only few sites with low defoliation levels in the eastern cluster showed climate-growth responses to maximum temperatures and water balance comparable to the western clusters. Several sites from the west and central clusters showed negative responses of growth to minimum February temperatures. Decreasing growth deviations with respect to the climate baseline were the most common pattern in western sites. In eastern and central Pyrenees, we detected a mild growth limitation by low soil moisture during the late growing season and positive growth recovery in recent years with respect to a climate baseline. Our results portend systematic spatial variability of growth trends across the Pyrenean silver fir populations forming the south-western distribution limit of the species in Europe. Decoupling of growth between eastern and western populations observed in the recent decades suggests contrasting vulnerability to climate change. More importantly, the decoupling of growth patterns from the climate baseline in western clusters could be used as an early-warning signal of impending dieback. Consequently, we foresee future dieback events to have more detrimental effects in the western compared with the eastern Pyrenees. The use of the Vaganov-Shashkin model or other tools to calculate growth deviations with respect to a climate baseline could be further explored to: (i) evaluate post-dieback growth recovery, and (ii) detect emerging forest dieback hotspots.

X-ray CT scanning for dendro research: examples from the UGent X-ray CT Core Facility (UGCT)

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The UGCT, or UGent Center for X-ray Computed Tomography, is a Core Facility of Ghent University. The Facility currently houses 6 X-ray CT systems, 5 of them custom-built and 1 commercial, each with their specific functioning. In addition, there is also a dedicated experimental set-up, used as a test-bed for novel detectors, scan geometries, etc. By means of a number of examples, 5 of the systems are presented for their specific use within forestry, wood anatomy and dendrochronology research. The Nanowood X-ray CT system is already 15 years old, and has been designed specifically for wood research at large. One of the specific complementary features to the other systems, is its sub-micron resolution capacity (down to ~0.4 micron) of low density materials. The system is typically good for anatomical scale scanning. Closest relative is Medusa, also a near sub-micron resolution system (down to ~0.6 micron), that has been equipped with a grating interferometry set-up for sub-resolution imaging, which is still highly explorative and a fundamental and unique implementation at lab-scale. HECTOR, which has been the work horse of the facility for many years, has been used extensively for tree-ring analyses of increment cores, logs, wooden boards, etc. It can carry objects up to 100kg, of objects up to 1m in height, and has a high flexibility in sample dimensions and resolution (down to ~3 micron). CoreTOM, its closest relative and the only commercial CT scanner of UGCT, has similar features and use, with a special focus on high-throughput scanning and reconstruction (resolution down to ~3 micron). EMCT, the Environmental CT scanner, is the odd duck, especially useful when lots of peripheral equipment (pumps, sensors) need to be installed on the object under study, because contrary to the other systems, source and detector can rotate infinitely around the object (resolution down to ~5 micron). A single 360° rotation can be done in 12 seconds, delivering the capacity of fast tomographic imaging of dynamic processes. It is as such used for example in cavitation research of small trees, plants and crops. These examples show the potential for dendro- and wood research at UGCT.

Delta-blue tree-ring chronologies of yellow pines (*Pinus jeffreyi* and *P. ponderosa*) in the Tahoe Basin of the Sierra Nevada, USA

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Advances in tree-ring analysis have demonstrated that multi-proxy records can reveal ecophysiological responses to environmental factors over multiple decades. Knowledge acquired from such studies is needed for science-based conservation strategies of tree-dominated ecosystems, from forests to woodlands. We developed chronologies of delta-blue measurements from yellow pines (*Pinus jeffreyi* and *P. ponderosa*) sampled at four sites within or near the Tahoe Basin of the Sierra Nevada. Dominant trees were selected to represent a range of stand conditions, from "sensitive" (low density with limited understory, sloping terrain with shallow soil, single dominant species) to "complacent" (deeper soils, higher density with dense understory, a few dominant species). Increment cores were mounted and mechanically sanded, then left in pure acetone at room temperature for 72 hours, and finally polished by hand. Images were obtained with a resolution of 2400 dpi using an Epson Expression 12000XL-GA as hardware, and Silverfast 8.8 as software. Color calibration was performed using IT8.7/2 reflective targets from LaserSoft Imaging. Delta-blue values, which are based on the difference between earlywood and latewood blue intensity, were computed using Coorecorder/Cdendro v. 9.6. Time series were combined together by site, and the delta-blue chronologies were then compared to chronologies of earlywood and latewood width. Our results shed new light on the potential of reflected blue light as a tree-ring proxy for conifer species of the western US, particularly when samples are obtained from forest interior sites in mountain environments.

Blue light from dark flames. Evaluating the potential of subfossil oaks for Blue Intensity analysis

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Nowadays Blue Intensity (BI) of coniferous tree species is a well-established method in dendrochronology. Several studies highlighted the benefits of BI, as a proxy of wood density, for dating purposes or environmental reconstructions. However, the most frequent tree species found in archaeological excavations or in gravel pits in temperate Europe is oak (*Quercus* spp.). This species is the basis of most of the tree ring calendars of central Europe and provides one of the most extensive tree ring chronologies. However, drawing conclusions about past growing conditions based on tree-ring width measurements of these oaks might be challenging due to their growing under more or less optimal conditions, which reduces the sensitivity of tree growth to environmental influences. Against this background we test whether methods of BI-dendrochronology can be applied to subfossil oaks that pose special challenges. In comparison to conifers, the wood anatomy of oaks is more complex, resulting in more tree-ring characteristics, which could potentially be analysed with BI-methods. The subfossil wood has survived due to special conditions, which preserved most of the wood substance but also has changed it, like colour changes in the wood tissue, which may bias the measurement of blue light reflection. We tested different chemical treatments to remove biochemical tanning agents and inorganic impurities. Therefore, we subsampled our main samples and treated them with different chemicals to see how these treatments influenced the BI-measurements. Lastly, we compared our BI time series against tree ring width and stable carbon and oxygen measurements of the same samples, to investigate how the different tree ring properties relate to each other. We examined a dozen subfossil oaks from a site in Western Germany, TRW dated to around 4400 BCE. With regards to wood anatomical features of oaks, we defined four characteristics, which could be analysed with BI-methods: lumen of earlywood vessels, earlywood fibers, latewood vessels (“bright flames”) and latewood fibers (“dark flames”) and focused on cross-dating as well as building a floating BI-chronology. We found out that the so-called “dark flames”, constituting the structures of highest density, are most promising for our analysis.

Developing of a long Blue Intensity based conifer chronology for the Solovetsky Archipelago (Russia)

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In the last decades the vast tree-ring network was developed in the Solovki Islands and is consisted of living tree material, architectural wood and drift-wood. A delta blue Intensity (dBI) were measured for 363 tree-ring samples. The dBI measurements of 185 tree-ring series of living conifer trees were combined into regional chronology since both conifers showed the same positive sensitivity to summer temperatures. dBI series obtained from historical buildings (131 samples) were successfully cross-dated against regional chronology and as a result chronology starts since 1186 CE. Since EPS >0.85 starts in 1417 CE, a drift-wood were used as another source of wooden material to increase the length and sample size of the chronology. Drift-wood material were collected from the Northern shore of the Anzer Island. Most of the trees were located at the first sea terrace, and only 10 trunks covered by mosses were located at the second sea terrace. The dBI measurements for the 1st terrace drift-wood were cross-dated and the tree death dates range between from the beginning to the middle of the 20th century. Despite the modern age, some samples showed more than 300 years length which is increased the replication in the chronology. Nevertheless 5 drift-wood samples showed promising dating results. Dates of death range from beginning to the middle of the 19th century. We also have showed how differs our cross-dating results when using two parameters - dBI and ring-width. It was shown that dBI series of drift-wood significantly better cross-dated.

Optimal window parameters in CooRecorder for measuring Blue Intensity of conifer tree rings along a latitudinal gradient in European Russia

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Blue intensity (BI) is a relatively new parameter measured for conifer tree rings. BI is relevant to dendroclimatology and tree-ring dating, and is gaining popularity because of potentially high recorded climatic signal at relatively low cost of measurements. BI can be measured in various software products as well as with various settings of the software. However only a few studies explored the dependence of the resulting proxy on the software settings, and these studies are all local. Here we use CooRecorder program and a set of 20 combinations of window parameters (width, offset, depth, percentage of selected pixels) for six locations situated along a latitudinal gradient in European Russia (43 to 65 degrees North). The optimality of a specific set was based on interseries correlation and the strength of climatic signal in each location. We explore how the optimal set of window parameters depends on the characteristics of tree growth and of the sites where they grow.

Impact of disturbance signature on ring width and blue intensity chronology structure and climatic signal in Carpathians Norway spruce

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Both climatic and non-climatic factors can influence tree radial growth, which can complicate the extraction of climate signals from tree rings. We investigated the influence of disturbance on tree-ring width (RW) and latewood blue intensity (BI) chronologies of Norway spruce from the Carpathian Mountains to explore disturbance impact on temperature signals in tree rings. Overall, ~15000 high-elevation Norway spruce tree cores from 34 sites grouped into four regions (Slovakia, Ukraine, North and South Romania) were analysed. The curve intervention detection (CID) method was applied to detect and correct potential disturbance trends. RW chronology structural comparisons were performed among disturbance-affected and disturbance-corrected chronologies for various spatial (regional / site) scales and sampling subsets. Structural comparisons were also performed for RW and BI chronologies developed from separated groups of series for five sites which exhibited clear disturbance trends. Temperature sensitivity was assessed for all chronology variants of both parameters. Results showed disturbance trends only affected RW chronologies at site / subset scale with relatively small series replication and were not detectable at regional scale. BI chronologies were generally unaffected by disturbance. BI data also contained much stronger growing season temperature signals, which appeared to be both spatially and temporally more coherent. Whereas highly replicated and spatially extensive datasets can help minimize or eliminate disturbance trends in RW chronologies, this potential influence should be considered when interpreting climatic signals in tree rings and reconstructing historical climate in weakly replicated periods. On the other hand, BI is a promising alternative tree ring parameter with stronger and more stable growing season temperature signals, whose seemingly disturbance-free chronology structure does not appear to suffer from this ecological bias, and therefore represents a more suitable parameter for dendroclimatological research.

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Does Divergence exist in white spruce tree-ring chronologies in the Yukon?

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From an expansive white spruce network of 86 ring-width (RW) chronologies from the central and southern Yukon, Latewood Blue Intensity (LWB) has so far been measured from 27 sites. This network includes samples from the 2022 field season with a primary aim to create an updated and revised climate reconstruction for this region in North America, but with particular emphasis on exploring “divergence-like” issues which have long been observed in RW studies using spruce across NW North America.

We theorise that “classic” divergence, often stated as a weakening in response and/or a decreasing trend in the recent period, is one aspect of a complex story of variable response between tree-ring parameters and climate. To investigate whether there are temporal instabilities in the updated Yukon network, we utilised RW and LWB information from 27 sites including both the recent collection of samples, as well as existing data gathered between 1997 and 2004. Principal component analysis (PCA) of the sites identified three initial groupings in the network. These groups were further refined using individual site response to climate, spatial distribution in the network, and site elevation, to create regional composite chronologies for further analysis. This refinement identified four distinct regional groups which are generally defined by a northern upper treeline group, a southern upper treeline group, a low elevation group expressing no temperature response, and another low elevation group expressing a fading temperature response. Correlation response function analysis (CRFA) identified June-July-August (JJA) maximum temperatures as the dominant season of response for the LWB, with an exception to the lower elevation group which demonstrates a slightly broader season of optimal response. RW data show strongest correlations with June-July Tmax.

Split period CRFA and running Spearman's correlations were used to explore the stability of the regional chronologies' response to temperature over time. The RW regional chronologies show clear evidence of significant temporal instability in tree-growth climate response, particularly in the northern and low elevation groups: we would therefore advise caution for utilising RW for dendroclimatic reconstruction in this region. The LWB chronologies display more subtle

signs of instability which are statistically not significant from the early 20th century through to present but are still intriguing. For example, the southern group shows a slight improvement in correlation with JJA through time (1901-1944 $r = 0.52$ / 1945-2021 $r = 0.67$), while the northern group shows the opposite trend (1901-1944 $r = 0.67$ / 1945-2021 $r = 0.58$). Although these subtle correlation changes may represent true physiological response changes, we must also respect the fact that the regional instrumental record prior to 1944 is derived mainly from one long station record at Dawson city which is geographically situated within the northern group. The two low elevation groups suggest that elevation (or distance from tree line) is also an important factor. Generally, high elevation sites $>1100\text{m}$ demonstrate a strong correlation between LWB and JJA T_{max} , a relationship that weakens as elevation decreases until we see no response at elevations $<800\text{m}$. The high elevation sites also show much less climate response instability over time. We hypothesise that the high elevation sites have expressed a stable temperature limitation over the last 120 years, while lower elevation sites demonstrate a weakening in temperature limitation on growth due to regional warming. We conclude by stressing the importance of using such a dense network of sites with varying elevations to understand “divergence”. Our results so far demonstrate that a robust LWB reconstruction can be developed for the region, so long as high elevation sites are utilised.

Using Blue Intensity on Drought-Stressed *Pines Sylvestris* from a Northern Swedish Site

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We have collected a large number of samples from living and dead *Pinus sylvestris* in the high coast region of northern Sweden (63.1°N, 18.5°E), which we aim to use for reconstruction of past hydroclimate. Due to the extensive post-glacial rebound in the region after the last ice age the highest coastline in the area is almost 300 metres. Despite being quite hilly, our entire study area has been under water at some point in the last 10,000 years. This has led to drought-prone conditions, as the fine sediments have been washed away. The forest on the hilltops tends to be sparse and sun-exposed with plenty of bare rock, and in some of the valleys there are extensive shingle fields.

Because of these soil conditions, many trees here tend to be drought-stressed even though the area receives a fair amount of precipitation (700-800 mm year⁻¹). We have collected samples from three sites in untouched forest that show little impact of human activity despite nearby settlements, likely due to a somewhat inaccessible terrain.

A chronology is now under development with the focus on using Blue Intensity from high resolution images (6000 dpi), using the new Skippy system developed at WSL. Initial results from the living trees are promising, showing severely suppressed tree-ring and latewood width as well as low density values during years with relatively low precipitation. We believe that there are good possibilities to develop a millennium-long hydroclimate reconstruction using the extensive amount of dead wood collected. And while several prominent temperature reconstructions originate from northern Sweden, a hydroclimate reconstruction from such high latitudes is rather unique and will fill an important gap in our knowledge of the climate of the past.

Variance Optimised Delta Blue Intensity

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Delta Blue Intensity (DB) was introduced by Björklund et al. (2014) to correct for potential colour biases that could impact Blue Intensity data measured from conifers that express a notable colour change from heartwood to sapwood. DB is generated by subtracting latewood blue intensity (LWB) from earlywood blue intensity (EWB) values to create a delta variable where the heartwood/sapwood colour change is minimised or removed. DB has been shown to perform well for several species such as *Pinus sylvestris*, *Pinus uncinata* and *Tsuga mertensiana*. However, DB does not always work, and the reasons for this failure has had little attention. The DB variable is a function of the variance structure of both EWB and LWB but also the climate signal expressed by both these parameters. For most conifer species from high elevation/latitude temperature limited forests, the strongest climate signal (summer temperatures) is seen in LWB which generally expresses greater variance than EWB. DB therefore represents the high frequency variance signal of LWB, but the delta calculation theoretically removes the common lower frequency colour trend of both variables. However, the ratio of the variance between LWB and EWB changes between both site and species, which adds ambiguity to the derivation of DB. Further, the climate signal represented by EWB and LWB may also vary between site and species again potentially impacting the climate signal expressed in the DB parameter.

In this study we present the concept of “Variance Optimised DB”. We experiment with an iterative procedure where the variance of EWB and LWB are adjusted upwards/downwards by increments of 1% before the delta calculation is performed. This results in 201 DB chronology variants reflecting the theoretical transition from EWB to DB to LWB. For example, EWB essentially reflects when the variance of EWB is set at 100% and LWB at 0% and vice versa for LWB. “Classical” DB is where the variance of both parameters is the same at 50%. These 201 adjusted DB variants are detrended using an age dependent spline (ADS with positive trend retention) and correlated against a relevant seasonal climate target. In so doing, it is possible to identify the optimal “adjusted” DB variant to represent that climate target. Initial experiments are presented using small regional networks of *Pinus sylvestris* from northern Scotland (6 sites) and *Tsuga mertensiana* from the Gulf of Alaska (4 sites). For the Scottish sites, mean July-August temperatures were the target climate parameter and the period 1901-2000 used for variance adjustment. The resultant six site chronologies were standardised to z-

scores over the 1866-2011 period and averaged to create a regional composite record using both “classical” DB and “adjusted” DB. The calibration r^2 of the “classical” DB regional record with JA temperatures is 0.61 (no signal free (SF)) and 0.65 (with SF). The “adjusted” DB regional records shows modest improvement at 0.65 and 0.67. Over the independent instrumental period (1866-1900), the validation r^2 is 0.61 (no SF and with SF) using “classical” DB, and 0.64 and 0.65 for “adjusted” DB. For the Gulf of Alaska example, 1901-1990 was used for the variance adjustment. The “classical” DB regional ADS chronology composite calibrates with r^2 values of 0.28 (no SF) and 0.33 (with SF) while the equivalent calibration results using “adjusted” DB are 0.36 and 0.41. Using an extended calibration period (1901-1998), the results improve for all variants to 0.33, 0.40, 0.44 and 0.48.

From these initial experiments, Variance Optimised DB appears to provide modest improvements of about ca. 5% explained variance over “classical” DB. For the Scottish example the average variance ratio adjustment of EWB vs LWB was a decrease/increase of ca. 30%, while for the Gulf of Alaska the value was ca. 40%. However, there was substantial variability in the adjustment between individual sites. Further ongoing experiments will be presented at TRACE 2023.

Using Elevational Transects to Explore Drivers of Divergence: A Scottish Case Study

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We utilise an elevational transect of 43 Scots pine chronologies ranging from upper treeline (ca. 550 masl) down to sea level from eastern Scotland to explore the climatic controls on growth with elevation. The mean elevational difference between each site is ~15 m with July-August (JA) temperatures at the lower elevation sites being ~3 °C warmer than at upper treeline. We hypothesise that lower elevation sites can be used as analogues for how higher elevation sites may respond in a warming world. High elevation ring-width (RW) chronologies generally express a relatively weak and temporally unstable positive correlation ($r = \sim 0.5$) with Jan-Aug mean temperatures which weakens towards lower elevations. Delta Blue (DB) Intensity chronologies express strong correlations (> 0.7) with July-August temperatures at high elevations which also weaken towards sea level. Sub-period modelling identifies optimal and temporally stable response between DB and JA temperatures for higher elevation sites with summer temperatures < 12.5 °C (roughly equivalent to > 400 masl). Similar strong results are also found for sites with summer temperatures between 12.5 and 13.5 °C (~ 250-400 masl) although some sites express a weakening in response over the last 20 years. For sites between 100 and 250 masl (13.5-14.5 °C), a weakening in response is noted since the 1970s while for sites below 100 masl (> 14.5 °C) correlations started falling around the 1920s, and since the 1970s have expressed no significant relationship with summer temperatures. Composite time-series of these four elevational groups show that the two higher elevation groups track summer temperatures very well, explaining well over 50% of the July-August temperature variance although some sites between ~250 and 350 masl show a slight decreasing trend over the last 10-20 years. The two lower elevation groups show a marked decrease in trend since the 1990s. Our analysis shows that DB chronologies from sites above 350 masl are currently robust strong temporally stable proxies for past summer temperatures. However, our modelling indicates that with a 1 °C warming this elevation threshold will rise to > 500 masl. Although there are multiple pine woodlands at these higher elevations, the sub-fossil material sampled in the region were sampled from lakes between 260-400 masl, suggesting that in periods when temperatures for these localities were > 13 °C, divergence-like weakening in response and associated declines in trends could well bias the data extracted from sub-fossil material. Our results show that so-called “classical” divergence (loss of temperature response and decreasing chronology trends) is extant in lower elevational locations in Scotland and are related to a weakening of temperature limitation in a warming world.

***Picea schrenkiana* tree ring blue intensity reveal recent glacier mass loss in High Mountain Asia is unprecedented within the last four centuries**

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Studies of long-term fluctuations in glacier volume and mass are important for understanding past climate change. In this paper, we used *Picea schrenkiana* to develop a 525-year chronology of latewood blue intensity (LWBI) in the Tianshan Mountains. Relying on temperature as the main controlling factor for tree growth and glacier mass balance (GMB) change, the LWBI chronology was used to reconstruct the summer temperature (JJA, $R_{2adj} = 47\%$) and the annual glacier mass balance (annual GMB, $R_{2adj} = 39\%$) in the Tianshan Mountains over the past 400 years. The reconstruction results show that the rapid warming since 1974 has caused the Tianshan No. 1 glacier (TS No.1) to experience an unprecedented melting trend within the last four centuries. The air-sea interaction, solar cycle change, and potential strong volcanic eruption make the glacier mass balance of Tianshan No.1 Glacier fluctuate interannual and interdecadal. It is disturbing that the glacier still remain in an ablation state for the next 80 years under both representative concentration paths (RCP) 4.5 and 8.5 scenarios, which will exacerbate the adverse environmental impacts of glacial hazards. Our study provides basic data for glacier research in high mountains Asian and shows a window of long-term fluctuations in typical mountain glaciers.

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