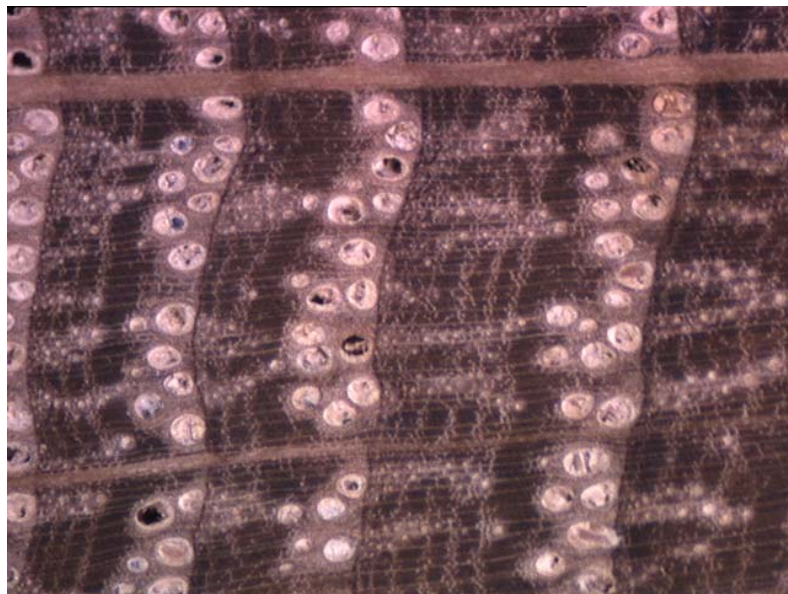


Universität für Bodenkultur Wien

**Annual and intra-annual variations of ring-widths and stable isotopes
in sessile oak (*Quercus petraea* (Matt.) Liebl.).**



Diplomarbeit

Martin Weigl

Eingereicht bei

Univ. Prof. Dipl. Ing. Dr. Rupert Wimmer

Institut für Holzforschung

Department für Materialwissenschaften und Prozesstechnik

Wien, im September 2006

About this theses

In February 2003 the European Project ISONET (Isotopic Synopses of Networked Environmental Trends; EVK2-2001-237) started with the aim to set up an isotopic network in Europe based on tree-rings, with a 400-year time scale and at an annual resolution. The ultimate purpose was to reconstruct climate variability in Europe using stable isotopes. I got the chance to work for this project as a laboratory technician in chemistry, a job I adopted beside studying “Wood Science and technology” at BOKU. During discussions with project partners I experienced the broad range of perspectives that existed within the project, which was due to the diverse background of the consortium. The good thing about bigger projects is that there is always space for new perspectives. This led me to the idea to contribute with some wood biology aspects to this project. After discussing this ideas with Michael Grabner, Rupert Wimmer from BOKU, as well as with Gerd Helle and Gerhard Schleser from FZJ, my contribution became finally part of work package 3 (Intra-annual isotopic variability and process studies).

After finishing my work I need to say that I was lucky with the selection of this particular topic as my thesis. It has certainly opened me a door to science.

Acknowledgement

This study was funded by the European project “ISONET, EVK2-2001-237” and received also support by the German Federal Ministry for Education and Research (DEKLIM-TRICE, 01LD00004). I like to thank the district forest managers Mr. Januskovecz, Mr. Janda and Mr. Buder for sampling permissions, Dagmar Holztröger, Melanie Schrimpf and Jussi Griessinger for their practical help with the isotopic measurement, Reinhard Böhm for providing meteorological data, and Michael Grabner, Gerd Helle, Gerhard Schleser and Rupert Wimmer for their continuous support and supervision. Last not least my deepest thank goes to my family for their caring support during the time of my studies.

Table of contents

1	Introduction	4
1.1	Ring-width.....	5
1.2	Stable isotopes.....	6
1.2.1	Carbon	7
1.2.2	Oxygen	10
1.3	Hypotheses	12
2	Material and methods	13
2.1	Site and tree.....	13
2.2	Samples	13
2.3	Ring widths	16
2.4	Preparation for isotopic analyses.....	17
2.5	Isotopic measurements	17
2.6	Climatic parameter	17
2.7	Statistical tools	18
2.7.1	Data treatment	18
2.7.2	Statistical analyses.....	19
3	Results	23
3.1	Axial variations	23
3.1.1	Identical calendar year	23
3.1.2	Identical cambial age.....	24
3.2	Radial variations.....	25
3.2.1	Relations along and between the tree-ring-parameter (widths and stable isotopes) ..	26
3.2.2	Climate-growth relationships	28
4	Discussion	31
4.1	Axial variations	31
4.1.1	Identical calendar year	31
4.1.2	Identical cambial age.....	32
4.2	Radial variations.....	32
5	Conclusion.....	39
6	Summary	41
7	Zusammenfassung.....	42
	References	44

1 Introduction

In temperate regions like middle Europe trees usually form annual rings. These tree-rings store information about climatic conditions, pollution, impact of human civilization and more. With proper tree selection and methodology this information may be extractable. The scientific background of analyzing tree rings is called *dendrochronology* (from Greek: δένδρον = tree, χρονος = time, λογος = lore; Cherubini et al. 2004). Dendrochronology covers a couple of methods like ring width- and wood density- measurements, chemical analysis as well as wood anatomical characterizations. Results of dendrochronological analyses may be of regional but also of global relevance.

Parameters such as percentage of latewood are usually determined at certain tree-heights and values may be comparable with those measured at other heights (Grabner & Wimmer 2006). However, Zhang et al. (1994) showed that wood density in oak varied more with cambial age, i.e. the number of rings counted from the pith, than with radial growth rates. The aging process of the cambium is primarily reflected in the rhythm of its pericline and anticline divisions, secondary effects such as initial cells length changes may also be good indicators (Bosshard 1974). Another secondary effect of cambial aging might be found with stable isotopic ratios. Only a few studies exist that have systematically investigated stable carbon isotope variations with stem heights (e.g. de Silva 1978). So far no systematic investigation looking at variations with stem height was published with respect to oxygen isotopes.

In dendroclimatology samples of living trees are usually taken at sites where an environmental variable (e.g. temperature or precipitation) is limiting tree growth (Schweingruber 1983). When wood samples are taken from historical constructions, from archaeological excavations, or from sub fossil findings, the principle of limiting growth does not apply. In addition, historical wood samples suffer from the fact that their within-tree positions are rarely known (Wrobel and Eckstein 2005).

Historical wood samples do not originate from defined tree-heights. Discrepancies might also exist with the radial orientation of cores. Samples for optimal dating should be free from reaction wood, meaning they are preferably taken from the uphill side when trees grow on steeper slopes, including also the outermost ring (Cook & Kairiukstis 1990). Radii of historical samples do not follow these criteria. Also due to their unknown tree sampling heights and radial directions, offsets in isotopic ratios between historical wood and samples from living trees may occur if they need to be put together.

Oak is a frequently utilized species in dendroclimatological studies using ring-widths as well as anatomical features or stable isotopes ratios as parameters (e.g. Hemming et al. 1998; Protoschill 1998; Loader et al. 2003; Mayr et al. 2003; Ogle et al. 2005; Pazdur et al. 2005; Sass-Klaasen et al. 2005; Eilmann et al. 2006). The potential of the tree-ring parameters to reconstruct past climate is demonstrated in a number of publications (e.g. Eckstein & Schmidt 1974; Baillie 1995; Helle 1996; Tardif 1996; Nola 1996; Zhang 1997; García González & Eckstein, 2003; Weigl et al. 2005).

Investigations of the intra-tree-ring variability of $\delta^{13}\text{C}$ -values in tree-rings revealed large seasonal fluctuations with a characteristic tri-phase pattern (Helle 1996; Helle & Schleser 2004). However, especially for $\delta^{18}\text{O}$ a lack of knowledge exists about the relative isotopic signature in intra-tree-ring structures such as earlywood, latewood, and in total tree-rings. Due to the ring-porous character of sessile oak splitting the ring into early- and latewood is an often applied practice with latewood used for the isotope analysis only (Borella et al. 1998).

1.1 Ring-width

Radial tree growth can be understood as the annual addition of a complete tissue layer deposited on top of the wooden body of the tree. As tree growth alters, changes can be seen in the wooden structure. For example, the appearance of distinct growth rings can be attributed to the interruption of the vegetation period during winter. The wood anatomical features depend on the species in the first place, but they are also affected by exterior factors. In case of a ring-porous species the cross-section shows several types of cells with earlywood and latewood clearly distinguishable: earlywood cells have thin cell walls and very wide lumen while latewood is built up by cells with narrow lumen and thick cell walls (Schweingruber 2001).

Widths of these tree-ring sections (early- and latewood) and accordingly total tree-ring are influenced by their position in the tree (e.g. roots, stem, branch, distance from the pith), and by conditions in the surrounding of the tree. Such exterior factors may be temperature, availability of water (in the liquid state in the soil or in the gas state as steam) sunlight, nutrients, wind, reduced space for roots, mechanical disturbances or air-, soil- and water-pollution (Schweingruber 1993), but also anthropogenic interference.

A tree-ring needs to fulfill three functions: conduction of water, mechanical stabilization and food storage. Under optimum conditions a continuous reduction of tree-ring widths occurs among others due to geometrical reasons while both functions still get fulfilled. This decline is the so called age

trend, which needs to be removed prior to statistical analyzes (e.g. Fritts 1976; Cook & Kairiukstis 1990; Helama et al. 2004). Deviations from this trend to wider or narrower rings occur due to exterior impact such as climate or population dynamic.

Within certain growth periods these deviations may be characteristic and they may also appear in the tree-rings of other trees. The procedure of comparing tree-ring sequences and putting them in relative positions to each other is called synchronization (Fritts 1976). If tree-ring records become synchronized against absolute dated chronologies (i.e. crossdating; Fritts 1976; Schweingruber 1983; Swetnam et al. 1985; Baillie 1995; Stokes & Smiley 1996) causes of these deviations may get absolutely dated by single events like e.g. volcanic eruptions (Fritts 1976; Schweingruber 1983, 1996, 2001) or climatic episodes such as summer droughts.

For further dendrochronological investigations only absolute dated or at least non dated but synchronized samples can be used. Dendrochemical investigations like the analyses of stable isotopes especially need to be carefully synchronized before preparation as for practical reasons samples often get pooled (Borella et al. 1998) and do not get analyzed separately.

1.2 Stable isotopes

Isotopes are different forms of chemical elements each having different mass due to different number of neutrons but same number of protons. Beside the 20 natural chemical elements (i.e. Be, F, Na, Al, P, Sc, Mn, Co, As, Y, Nb, Rh, I, Cs, Pr, Tb, Ho, Tm, Au, Bi), more than one isotope exist for all of the other natural chemical elements. While radioactive isotopes disintegrate under formation of other isotopes of the same or other chemical elements showing lower number of order, stable isotopes, however, do not disintegrate. In nature available isotopes show percentile relations with one outstanding isotope dominating significantly. For example carbon exists of 98.892% ^{12}C and 1.108% ^{13}C (Latscha et al. 1988), while oxygen has 99.76% ^{16}O and only 0.24% ^{18}O .

In trees, stable isotopes of the same chemical element may deviate from concentrations found in the environment due to fractionation processes that can be understood as selective discriminations of isotopes (Farquhar et al. 1982). Some fractionation procedures are due to climatic or microclimatic conditions others caused by biochemical processes. For this reason the relative differences of stable isotopes of one chemical element found for example in cellulose or in total wood can be used to reconstruct climatic conditions in former days (see below).

The relations of stable isotopes are usually given as δ values referring to a standard substance given in per mill:

$$\delta^{13}\text{C} = ((^{13}\text{C}/^{12}\text{C}_{\text{sample}})/(^{13}\text{C}/^{12}\text{C}_{\text{standard}})-1)*1000 [\text{‰}] \quad (1)$$

$$\delta^{18}\text{O} = ((^{18}\text{O}/^{16}\text{O}_{\text{sample}})/(^{18}\text{O}/^{16}\text{O}_{\text{standard}})-1)*1000 [\text{‰}] \quad (2)$$

Positive δ -values can be understood as isotopic heavier conditions in the sample than in the standard (Treydte 2004). Values measured on organic tree-ring-mater are usually positive for $\delta^{18}\text{O}$ and negative for $\delta^{13}\text{C}$.

Originally, belemnites (*belemnoidae* are a group of extinct *cephalopod* belonging to the mollusk family) of the Pee-Dee-formation (i.e. a region in the US-state North-Carolina named by the Pee Dee river) had been used as standards for carbon-measurements (i.e. Pee-Dee-Belemnite [PDB] - standard) and ocean-water-standards for measurements of oxygen (SMOW – Standard Mean Ocean Water). Nowadays international standards that were calibrated to these standards are provided by the IAEA (International Atomic Energy Agency) wearing the names Vienna-PDB (VPDB) and Vienna-SMOW (VSMOW). Laboratories usually use there own standards that were calibrated to VPDB and VSMOW (Treydte et al. 2004).

1.2.1 Carbon

The source of carbon for organic matter in trees is atmospheric CO_2 . Variability of atmospheric CO_2 -concentration and -isotopic composition have impact on the isotope pattern of tree-ring matter. For this reason it's important to take a look on recent CO_2 -measurements and measurements carried out on ice cores.

Isotope composition of atmospheric CO_2 is not constant with time. Figure 1 (Treydte et al. 2004) shows a clear global exponential decrease of $\delta^{13}\text{CO}_2$ with a range of about 1.5‰ within the last 250 years.

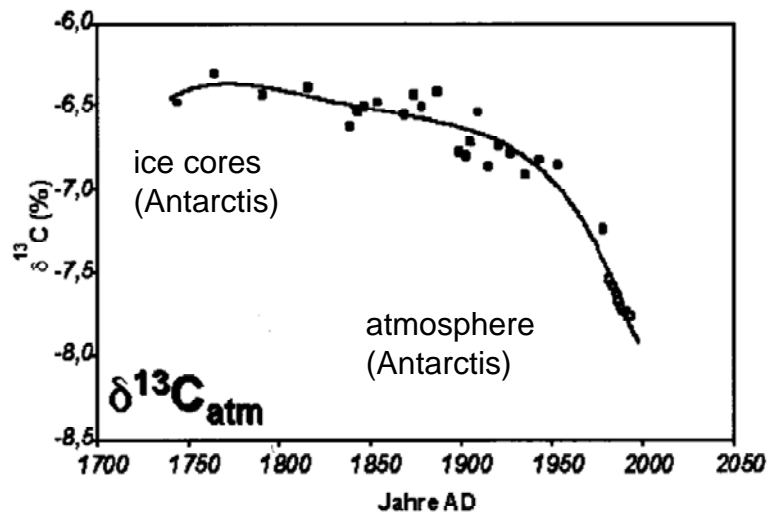


Figure 1: Exponential decrease of $\delta^{13}\text{C}\text{O}_2$ (Treydte et al. 2004).

Also atmospheric CO_2 -concentration changed remarkably within the last centuries. Treydte et al. (2004) report an exponentially increase of atmospheric CO_2 -concentration during the past 250 years with a range of about 80ppm (Fig. 2).

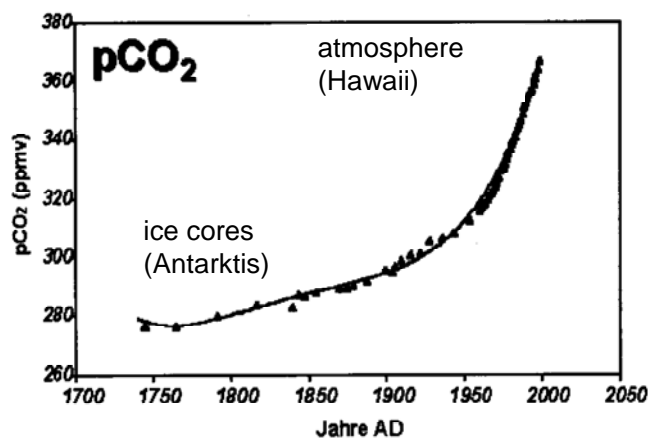


Figure 2: Exponential increase of atmospheric CO_2 -concentration (Treydte et al. 2004, modified).

Burning of fossil fuel leads to these two trends. Fossil fuel in general shows lower concentrations of ^{13}C than modern CO_2 (coal and mineral oil: -22 to -28‰, natural gas: -35 to -48‰ (Stuiver 1978)). This caused a change of atmospheric $\delta^{13}\text{C}\text{O}_2$ from -6.5 to -8‰ within the 20th century (Treydte et al. 2004).

Effects of changing CO_2 -concentrations and isotopic compositions on measured values can be eliminated for example by the use of the corrections of Francey et al. (1999) and Keeling et al. (2005).

Atmospheric CO₂ has to overcome several types of diffusion-resistances on its way through the stomata (i.e. the gas exchange organ of a leaf) into the interior section of the leaf where the photosynthetic active chloroplasts are situated in the protoplast. The degree to which ¹³C gets discriminated depends on a) the aperture of the stomata or there conductivity and b) on the photosynthetic rate (Farquhar et al. 1989).

The resistance is lower for ¹²CO₂ than for ¹³CO₂ during uptake into the leaf, meaning that the molecules carrying lighter isotopes are faster. The enzyme RubisCO, which is located in the chloroplasts and is responsible for the turn over of carbon from CO₂, gives preference to the lighter ¹²C-isotope respectively discriminates the heavier ¹³C-isotope. This fractionation while carboxylation (ϵ_C) is much stronger than compared to the fractionation while diffusion into the chloroplasts (ϵ_D) (Roeske & O'Leary 1984). The more CO₂ is available ¹³C gets more discriminated.

Under cool and humid conditions (Fig. 3, left picture) stomata are widely open leading to almost equal concentration of CO₂ inside (C_i) and outside the leaf (C_a) and a high transpiration. This causes a huge impact of photosynthetic fractionation (Δ) on the total fractionation. Under warm and dry conditions (Fig. 3, right picture) stomata are more or less closed leading to a big difference in concentration of CO₂ inside (C_i) and outside of the leaf (C_a) and a reduced transpiration. This causes a smaller impact of photosynthetic fractionation (Δ) on the total fractionation.

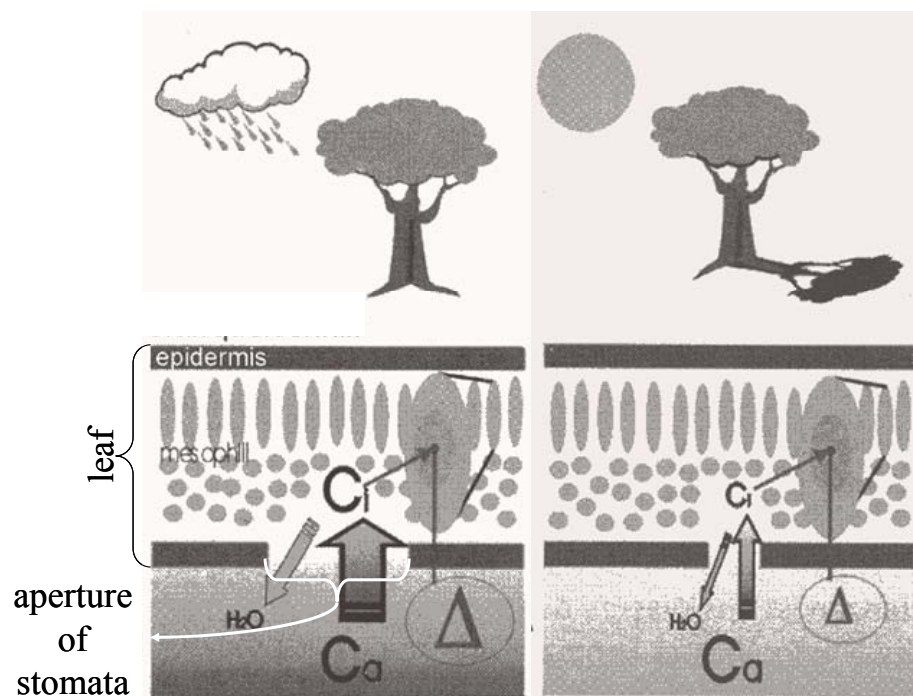


Figure 3: Fractionation processes of ¹³CO₂ (Treydte et al. 2004, modified).

Equation (3) shows the influence of exterior and interior conditions on the ^{13}C -composition of plant mater a little more detailed (Treydte et al. 2004):

$$\delta^{13}\text{C}_P = \delta^{13}\text{C}_a + \varepsilon_D(1-c_i/c_e) + \varepsilon_C(c_i/c_e) \quad (3)$$

$\delta^{13}\text{C}_P$ ^{13}C -composition of the plant

$\delta^{13}\text{C}_a$ ^{13}C -composition of atmospheric CO_2

ε_D diffusion-resistance

c_i/c_e relation of CO_2 -concentration inside the leaf (c_i) to exterior conditions (c_e)

ε_C resistance while carboxylation

Treydte et al. (2004) give two examples for conditions leading to the most different values for $\delta^{13}\text{C}_P$:

- a) Under cool and humid conditions (left picture in Fig. 3) c_i/c_e is almost 1. This leads to very low values for $\delta^{13}\text{C}_P$ as it gets almost only influenced by ε_C .
- b) Under warm and dry conditions (right picture in Fig.3) lower values for c_i can be found that causes a loss of importance of ε_C and a win of importance of ε_D . Under these conditions $\delta^{13}\text{C}_P$ reaches high values.

1.2.2 Oxygen

The source of oxygen in organic mater of trees is water, which gets taken up by the root system. It may be taken in directly after rainfall, from ground water or from sources in the soil. Figure 4 shows the different possible water reservoirs. While water at the surface almost shows the isotopic oxygen composition of actual rain water ($^{18}\text{O}_N$), water from deeper layers (soil [$^{18}\text{O}_{BW}$] and ground water [$^{18}\text{O}_{GW}$]) shows a more negative average. $^{18}\text{O}_{GW}$ represents long term climatic signals (Siegenthaler & Oeschger 1980; Saurer et al. 1995a).

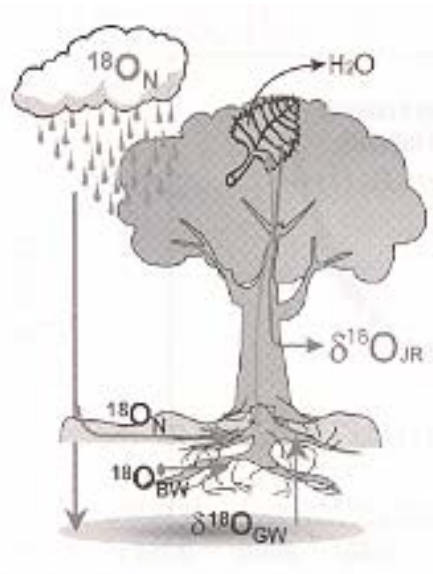


Figure 4: Water reservoirs with different isotopic composition for oxygen (Treydte et al. 2004).

Isotope composition measured in rain water is of special interest for climate research: Water vapor originating from ocean water rains out gradually while crossing land. As water molecules including heavy isotopes (e.g. H_2^{18}O) condense easier, rainwater enriches with heavy isotopes compared to the water vapor which always gets isotopic lighter. This effect of getting isotopic lighter water vapor always repeats itself so that local precipitation gets isotopic lighter with increasing distance from the site of evaporation (Treydte et al. 2004).

Treydte et al. (2004) name four effects influencing the isotope composition in rain water: the *continental effect*, meaning the above described effect of distance between evaporation and precipitation, the *latitude effect*, meaning changes from the equator to the pole, the *altitude effect* and the *quantity effect*.

While there appears almost no fractionation due to uptake of water by the roots and transport to the leaf (White et al. 1985), the O-isotope-composition of available water changes further during transpiration of leaves. Lighter isotopes can easier be evaporated leading to heavier leaf-water (Dongmann et al. 1974; Förstel 1978; Brenninkmeijer 1983; Yakir 1992). Strength of this effect depends very much on relative humidity, temperature and the isotope composition of steam in the surrounding air and on resistances at the stomata and on the leaf-air-transition zone (Craig & Gordon 1965). During photosynthesis also biochemical fractionations appear leading to a discrimination of ^{18}O (e.g. Yakir 1992). Also exchanges between xylem water and phloem sap are made responsible for shifts in O-isotope-composition (Saurer et al. 1995b, 1997).

Due to the complex processes behind fractionation of ^{18}O compared to ^{13}C , still a lot of questions concerning these mechanisms are not answered yet.

1.3 Hypotheses

To understand whether a pool of historical wood samples and samples from living trees can be used for climatically studies and which parameter could be the optimum selection the following hypotheses are stated:

- (1) Sampling height has an influence on measured values for latewood (LW)-width and LW-stable isotopes.
- (2) Calendar year has an influence on measured values for LW-width and LW-stable isotopes.
- (3) Cambial age has an influence on measured values for LW-width and LW-stable isotopes.
- (4) Data originating from historical wood can be combined with data from recent wood.
- (5) Ring-widths and isotopic ratios measured in complete tree-rings (TR), in earlywood (EW), in latewood (LW), and in so-called transfer tree-rings (TTR) show strong statistical relations to each other.
- (6) Ring-widths and isotopic ratios measured in complete tree-rings (TR), in earlywood (EW), in latewood (LW), and in so-called transfer tree-rings (TTR) show potential differences in their relation to climatic quantities.

2 Material and methods

2.1 Site and tree

A dominant 145-year old sessile oak tree (*Quercus petraea* (Matt.) Liebl.) with a height of about 30m was selected from a dry lowland oak site located at Lainzer Tiergarten, area between Pulverstampftor and Glasgrabenwiese, in Vienna, Austria (48°11'N, 16°12'E, 300 m a.s.l.). The site was also subject of earlier studies (Liebert 1996; Weigl et al. 2004, 2005, 2006) and closely located to the meteorological station at Hohe Warte, Vienna (48°25'N, 16°37'E, 203 m a.s.l.).

The site is characterized by a low slope of about 0 to 10°, a flat and shallow ground of brown soil built up on flysch. Roots have no contact to water reservoirs. The forest shows an open structure with partial gaps. Beside different oak species mainly beech (*Fagus sylvatica*), European Hornbeam (*Carpinus betulus*) and Ash (*Fraxinus excelsior*) are stocking at this site. The tree was felled in January 2004.

2.2 Samples

The stem of the tree was cut into several 4 m logs. Cross-sectional disks were taken from each of the lower log ends to obtain samples from seven heights, i.e. at 0, 4, 8, 12, 16, 20 and 24 m. As the innermost 20 tree-rings showed distinct decreasing latewood-widths at the seven stem-heights, this section of the trunk was identified as juvenile wood and excluded from the analyses (Fig. 5).

The number of sapwood rings present at the disks was noted. For reasons of simplicity the maximum number of sapwood rings found was assumed to be constant across the tree heights. Sapwood was not analyzed due to the changing amount of total nonstructural carbohydrates such as starch and sugars (Barbaroux & Bréda 2002), which might affect isotopic values measured on wood. The remaining portion of the trunk actually analyzed was named “adult heartwood” (Fig. 5).

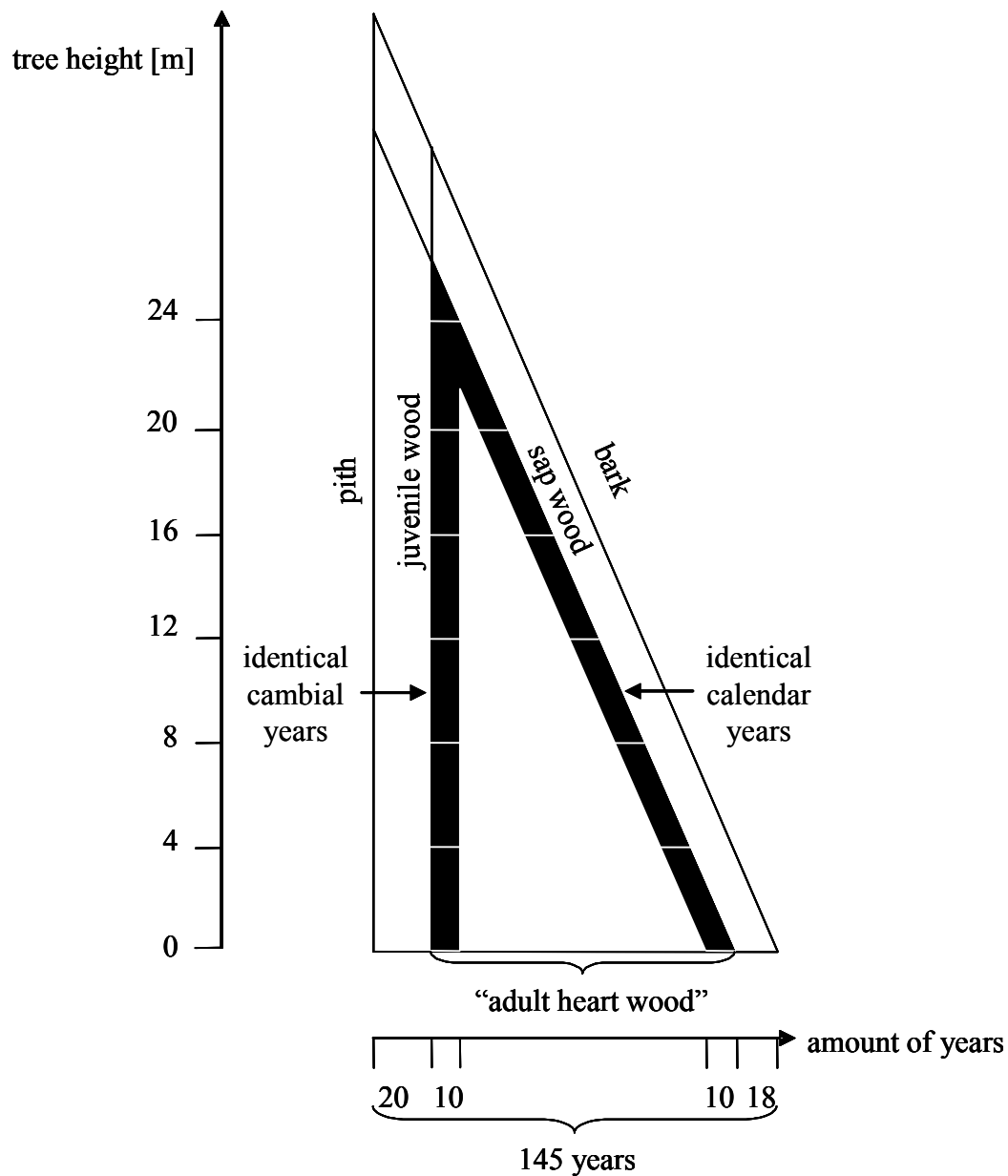


Figure 5: Right half of the trunk of the selected tree cut in the radial/axial layer. The broad black lines indicate areas of identical cambial ages (upright) and of identical calendar years (sloped). White lines give the position of the decadal samples.

Radial flawless segments were cut from the discs of all seven stem-heights. The segments were free from reaction wood and taken randomly around the stem circumference.

All samples were sanded with a 240 grid corundum sanding paper. To remove remaining corundum particles and dust the surfaces were cleaned with compressed air (800 kPa), followed by a visual control under a reflected light microscope.

From each of the seven segments a series of ten tree-rings including the calendar years 1976 – 1985 was cut. A second set of decadal ring series with identical cambial ages was prepared for each of the seven stem-heights. These were the innermost tree-rings belonging to “adult heartwood” covering the 21st to 30th tree-ring after the pith (Tab. 1, Fig. 5).

Table 1: Covered calendar years of the decadal sequences prepared from seven stem-heights with identical cambial age (21st to 30th ring after pith).

height [m]	0	4	8	12	16	20	24
Time span	1879 –	1894 -	1905 -	1918 –	1930 –	1947 -	1976 -
[year AD]	1888	1903	1914	1927	1939	1956	1985

Further more a 50-year sequence lasting from 1936 to 1985 was selected for the preparation of the four tree-ring parameters from the disc at 4m stem-height. Four tree-ring parameters were analyzed, i.e. earlywood (EW), latewood (LW), complete tree-ring (TR), and the so-called transfer tree-ring (TTR) (Fig. 6). The latter was defined by Weigl et al. (2004) to account for carry-over effects from one calendar year to the next (Eckstein & Schmidt 1974; García González & Eckstein 2003) by adding the following year EW to the current year LW:

$$TTR_t = LW_t + EW_{(t+1)} \quad (4)$$

As LW dominated the radial growth during the selected time period in this tree, it was expected that TTR-values, dated due to the calendar date of the corresponding LW-component, would represent climatic conditions comparably to other tree-ring parameter of same calendar date.

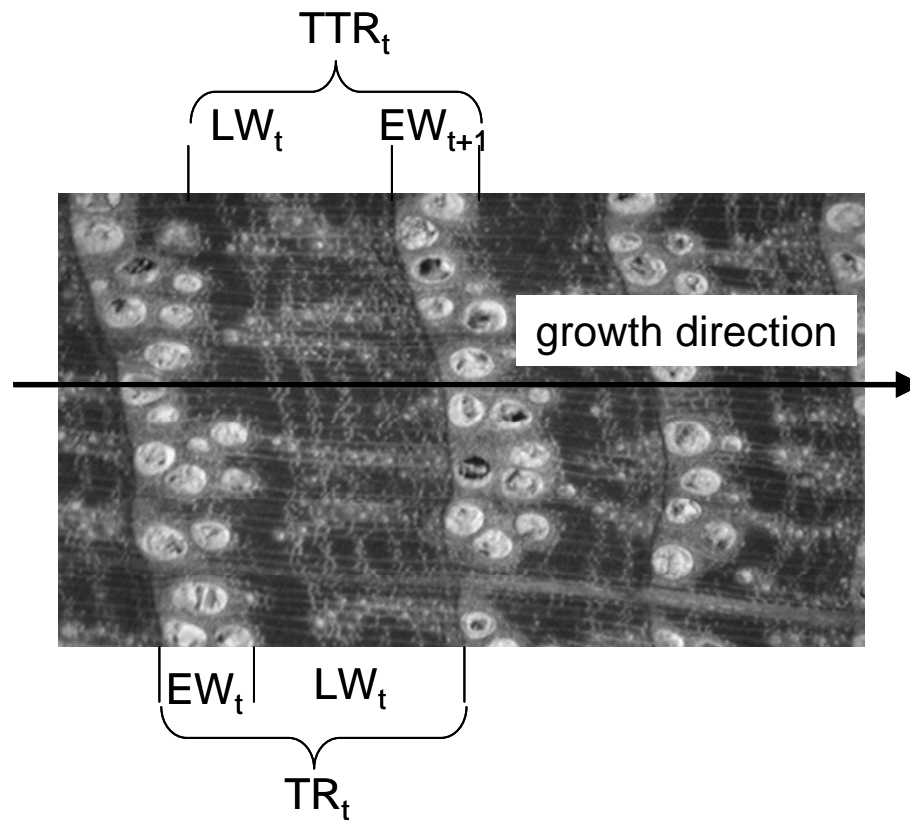


Figure 6: Tree-ring parameters showing earlywood (EW), latewood (LW), tree-ring (TR) and transfer tree-ring (TTR). The latter is the combination of LW from the current year t plus the EW from the subsequent year ($t+1$).

Three radial strips of 9 x 9 mm in tangential and axial direction were cut from the 50-year-sequence. The strips were located close to each other in longitudinal direction. The position of the radial samples on the discs was kept the same for both width- and isotopic- measurements. One strip was used to build up the EW- and the LW-series, the second one for the TR-series, and the third one for the TTR-series. These samples were also sanded, cleaned and controlled as described above.

2.3 Ring widths

Ring width measurement followed the direction of the wood-rays. As in oak wood rays are seldom perfectly oriented in radial direction samples had to be adjusted from time to time. Regions showing anatomically abnormalities like callus or tension-wood could not be used for analyses of radial growth.

EW- and LW-width-measurements were carried out using the LINTAB measuring device (www.rintech.de) running on the software TSAP-WIN 0.52 © (Rinn 2003). TR- and TTR-series were calculated based upon these measurements. All raw width-series were crossdated against the

Eastern Austrian oak chronology (Geihofer et al. 2005) using standard procedures (Holmes 1983; Swetnam et al. 1985; Rinn 1996; Stokes & Smiley 1996). Furthermore, all four width-parameters were synchronized with width-measurements of the identical tree-ring-section of 20 other trees from the same site (e.g. LWW_{site} vs $LWW_{\text{this tree}}$; Weigl et al. 2004).

2.4 Preparation for isotopic analyses

LW of each tree-ring of the selected decadal samples and EW, LW, TR and TTR of the selected 50-year sample were prepared by manual dissection under a stereo-microscope on a glass plate using razorblades.

All samples were ground and homogenized in a Retsch® ultra centrifugal mill (mash 0.75 mm). Homogenized wood samples of $260 \pm 40 \mu\text{g}$ each were weighed into tin capsules (for $\delta^{13}\text{C}$ -analyses) or into silver capsules (for $\delta^{18}\text{O}$ -analyses). $\delta^{13}\text{C}$ -samples were directly packed while $\delta^{18}\text{O}$ -samples were vacuum-dried at $60 \text{ }^\circ\text{C}$ for at least 24 h before packing.

Since isotopic ratios determined in wood powder show the same relative variations as isolated cellulose (Loader et al. 1997; Borella et al. 1998), measurements were carried out on wood only.

2.5 Isotopic measurements

Isotopic measurements were performed on a mass spectrometer (OPTIMA-IRMS GV-Instruments, Manchester) coupled on-line to an elemental analyzer (Carlo Erba). Merck®-cellulose powder and IAEA C3- (International Atomic Energy Agency) cellulose were used as laboratory standards and were run after a series of ten samples. In case of signal drift within a series the data were progressively adjusted. Values of $\delta^{13}\text{C}$ refer to VPDB (“Vienna Pee-Dee-Belemnite”) and $\delta^{18}\text{O}$ to VSMOW (“Vienna Standard Mean Ocean Water”). $\delta^{13}\text{C}$ measurements were done once, while replicates were performed for $\delta^{18}\text{O}$. The analytical reproducibility was $<0.1\text{‰}$ for $\delta^{13}\text{C}$ and $<0.3\text{‰}$ for $\delta^{18}\text{O}$.

2.6 Climatic parameter

Monthly mean temperature and monthly sums of precipitation and ^{18}O data from the GNIP (Global Network of Isotopes in Precipitation managed by the WMO [World Meteorological Organization] and IAEA) were provided by the Zentralanstalt für Meteorologie und Geodynamik Vienna (ZAMG).

Homogenized temperature- and precipitation-data were made available for the time period from 1936 to 1985 and GNIP-data from 1961 to 1985. Missing monthly data in the GNIP records were replaced by the average of the same month over the whole record (January 1962 and 1963, February

1972, April 1964, May and June 1979, July 1971, August 1971 and 1974, October 1965, 1968 and 1980, November 1968 and 1982 and December 1968, 1971 and 1972).

All GNIP-data were weighted by the corresponding monthly precipitation amount. During winter months (November to March) GNIP-data were measured on snow or on a combined sample of snow and rain, while during the rest of the year rain water could be sampled. This is of importance because snow shows up to 30‰ lower (i.e. isotopically lighter) $\delta^{18}\text{O}$ -values than rain water (Rozanski et al. 1992).

Simple correlations of ring-widths and isotope values with climatic parameters were calculated for the period from previous September to current September.

2.7 Statistical tools

Statistical values were calculated by using the publicly available software COFECHA (Holmes 1983, <http://web.utk.edu/~grissino/contents.htm>), TSAP (Rinn 1996, www.rinntech.de), SPSS 10.0 and DENDROCLIM2002 (Biondi & Waikul 2004, <http://woods.geography.unr.edu>).

2.7.1 Data treatment

Due to changes in the $\delta^{13}\text{C}$ of atmospheric CO_2 caused by burning of fossil fuels and deforestation along the 20th century a correction of the $\delta^{13}\text{C}$ -values was performed using data by Francey et al. (1999) and Keeling et al. (2005). The declination of $\delta^{13}\text{C}$ -values during the investigated time span from 1879 to 1985 is of about 1.2‰ (Mook et al. 1983, Francey et al. 1999).

For most of the analyses a 30-year spline was fitted to the width- and stable isotopic-data by the use of the ARSTAN40 software (Cook & Krusic 2005) to remove age related trends. For analyses of mean sensitivity z-transformation was performed on all the data in order to receive constant variability for all data. Equation 5 explains the procedure:

$$x_z = \frac{x_t - \bar{x}}{s} \quad (5)$$

x_z is the z-transformed value, x_t the measured value for the year t , \bar{x} the mean and s the standard deviation. This procedure was selected especially for comparison of values for mean sensitivity.

Due to the very different year to year variability of the various datasets (i.e. widths and stable isotopes), (Strackee & Jansma 1992) comparability without transformation would not be given. After transformation the mean value of each single time series shows the value 0 and the value at

standard deviation at the power of one equals ± 1 . As $\delta^{13}\text{C}$ -values usually show a negative algebraic sign, this transformation would lead to mirrored values along the time-axis. For this reason values of x_z for $\delta^{13}\text{C}$ got multiplied by -1.

2.7.2 Statistical analyses

The following statistics were performed for data analyses: *mean sensitivity*, *Gleichläufigkeit* (Glk), *t-values* (TVBP), *simple correlation*, *partial correlation* and *autocorrelation*. Estimation of autocorrelation was carried out on raw data while all other analyses were performed on standardized values. Standardization procedure was always 30-year spline except for analyses of mean sensitivity where z-transformation was selected.

2.7.2.1 Mean sensitivity

The relative difference from one year to the following can be described by the sensitivity. This parameter can also be understood as the mean percentage change from one yearly value to the next. Mean sensitivity (m_{sx}) is an average of sensitivities of the whole span of a time series. Values may vary from 0 for values followed by the identical value, up to 2 for 0-values followed by non-0-values (Fritts 1976). It can be calculated by the equation:

$$m_{sx} = \frac{1}{n-1} \sum_{t=1}^{t=n-1} \left| \frac{2(x_{t+1} - x_t)}{x_{t+1} + x_t} \right| \quad (6)$$

where x_t is the measured value for the year t and n the number of years (Fritts 1976, Schweingruber 1983, Strackee & Jansma 1992).

Mean sensitivity shows the strength of relationships between radial growth and exterior influencing parameters (Strackee & Jansma 1992). For comparison of data showing different standard deviation like widths and stable isotopes or widths and cell wall thickness, standardization of data is absolutely necessary (also there). Values of mean sensitivity were calculated using COFECHA (Holmes 1983).

2.7.2.2 Gleichläufigkeit

The intervals between consecutive points within a time series show upward or downward trends. “Gleichläufigkeit” (Glk) is a measure of the similarity of these trends between two synchronic time series. Glk can be calculated by the equation:

$$Glk_{(x,y)} = \frac{1}{n-1} \sum_{t=1}^{n-1} |Glk_{tx} + Glk_{ty}| \quad (7)$$

where x and y are the two time series, t is the calendar year and n the number of years (Schweingruber 1983). Commonly values are expressed as percentage. Values close to 100% indicate that two time series are identical in terms of the direction of their annual trends (Eckstein & Bauch 1969). With an overlap of 50 years (as performed for analyses of radial variations) Gleichläufigkeit becomes significant ($p < 0.05$) at 62% and highly significant ($p < 0.01$) at 67%. With an overlap of 10 years (as performed for analyses of axial variations) Gleichläufigkeit becomes significant ($p < 0.05$) at 76% and highly significant ($p < 0.01$) at 87%.

Values of Gleichläufigkeit were calculated by the use of TSAP Version 3.0 (Rinn 1996).

2.7.2.3 Simple correlation

Simple (Pearson) correlation is used to test the degree of association between two interdependent data sets. Results reflect direct and indirect relationships that do not imply causality. Strength of this association is described by the correlation coefficient r. It is calculated by the equation:

$$r_{x,y} = \frac{\sum_{t=1}^n (x_t - m_x)(y_t - m_y)}{(n-1)s_x s_y} \quad (8)$$

where m_x and m_y are the means and s_x, s_y the standard deviations of the two data sets x and y. Values range between +1, which indicates perfect and positive agreement, and -1, which indicates perfect negative agreement. 0 indicates that the two data sets are completely independent or at least non-linearly dependent.

Simple correlations were calculated by the use of the SPSS 10.0 statistical software program and DENDROCLIM2002 (Biondi & Waikul 2004).

2.7.2.4 Partial correlation

The Pearson correlation coefficient r might not describe correctly the relationships between two variables if both are influenced by the same one or more further parameter. Effects of such parameter can be filtered out using partial correlation by defining the suspected parameters as a so called control variable. The number of control parameter gives the order of the partial correlation coefficient r_p . In the easiest case just one control parameter z exists (i.e. first order) when the two variables x and y get correlated. The partial correlation coefficient could than be written as $r_{xy | z}$ (Kleinbaum et al. 1988).

For example $EW\delta^{18}O$ is highly significant simple correlated with LWW and also significant simple correlated with TRW (Fig. 8, middle). Using partial correlation on the relationship of $EW\delta^{18}O$ and LWW, the effects of TRW can be filtered out leading to a significant value of r_p (Fig. 8, right). In this case TRW functioned as a control parameter.

This procedure can be done as long as control variables originate from independent measurements. As TRW and TTRW were not independently measured, a possible effect of EWW on the partial correlation of LWW and TRW could not be filtered for example.

The strength of relations calculated by partial correlation is given by the partial correlation coefficient r_p covering values between +1 and -1.

Partial correlations were calculated by the use of the SPSS 10.0 statistical software program.

2.7.2.5 Autocorrelation

Autocorrelation describes how strong a time series correlates with itself when it gets shifted on the time axes. The number of years the series got shifted gives the order of autocorrelation (first order means a one year shift). A dependency of growth on previous years is revealed by significant autocorrelation values (Fritts 1976). Analyzes of autocorrelation were the only one performed on raw data as autocorrelation usually gets reduced by standardization (Fritts 1976; Cook & Kairiukstis 1990; Helama et al. 2004).

Autocorrelations were calculated by the use of COFECHA (Holmes 1983).

2.7.2.6 t-value

Whether the observed correlation coefficient r is significantly different from zero can be illustrated by the t-test. It is calculated by the equation:

$$t = |r| \sqrt{\frac{n-2}{1-r^2}} \quad (9)$$

where r is the correlation coefficient between the two data sets and n the number of year of the overlapping period.

Special modified t-values like the one of Baillie and Pilcher (TVBP) are used in dendrochronology for cross-dating (e.g. Baillie & Pilcher 1973). This method eliminates low-frequency variations in the time series as each value gets divided by the corresponding 5-year moving average. As a common practice, t-values have to reach a minimum of 4.0 and data must show a minimum overlap of 30 years for reliable dating. With increasing similarity of two time series t-values likewise increase up to values of 100 for identical series (Baillie & Pilcher 1973). t-values are the most commonly used statistical tool for comparing and cross-dating ring widths series. Here they are used for comparison of width- and isotopic-data. The t-values were calculated by the use of TSAP Version 3.0 (Rinn 1996).

3 Results

3.1 Axial variations

The average number of sapwood-rings over all stem-heights was 14.4 ± 1.72 . The maximum of 18 sapwood-rings was found at 24 m above ground. This part of the trunk already belonged to the crown.

3.1.1 Identical calendar year

A stem-height-profile for LW-widths and -stable isotopic ratios of identical calendar year is shown in Figure 7.

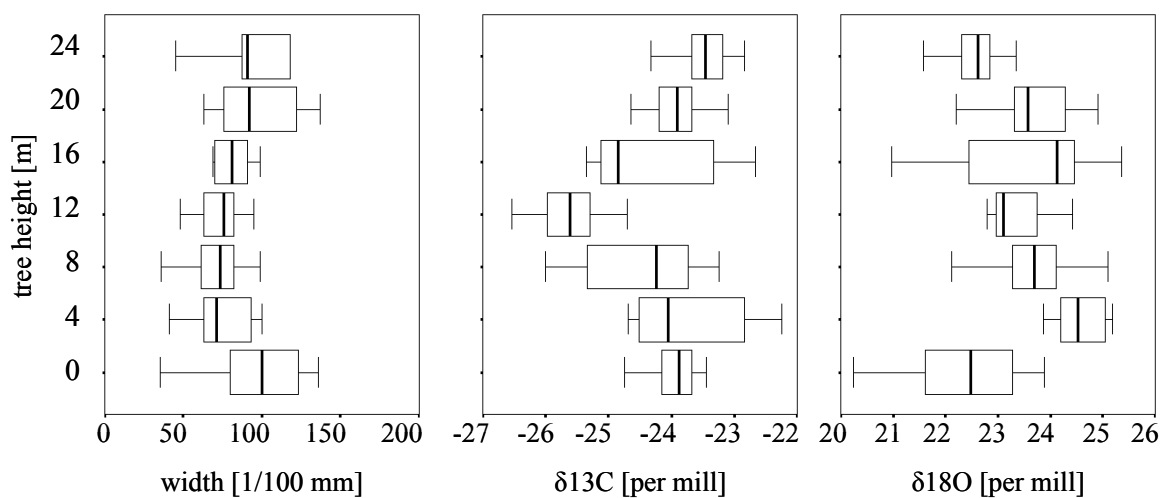


Figure 7: Box-whisker plots of LW-widths (left), $-\delta^{13}\text{C}$ (middle) and $-\delta^{18}\text{O}$ (right) from decadal samples covering 10 tree-rings ($n=10$) representing identical calendar years at seven tree heights. Boxes indicate quartiles and include the median. Whiskers give the 1.5-times interquartile distance from the end of the box.

Data show a trend towards wider latewood close to the stem basis (0 m) and higher up in the crown (20 and 24 m) while the central part of the trunk remains more or less constant (4, 8, 12 and 16 m).

This trend was even more pronounced with the $\delta^{13}\text{C}$ -values. Data show less negative $\delta^{13}\text{C}$ -values at the bottom and the top of the trunk and more negative ones in the center part of the stem. The $\delta^{13}\text{C}$ -values were most negative at 12 m stem-height.

$\delta^{18}\text{O}$ -values reflect a more complex picture. With the value at 0 m omitted, LW- $\delta^{18}\text{O}$ -values of identical calendar years would show a decline with stem-height from 4 to 24 m with a range of more than 1.5‰.

Comparison of LW-widths and -stable isotopic ratios covering identical calendar years across all stem-heights using simple correlation and Glk shows that strong relations exist within LW-widths (e.g. $r=0.78$ and $Glk=100\%$, comparing 4 with 12 m stem-height; Fig. 8) and also within each of the isotopic series (e.g. $r=0.93$ and $Glk=88\%$, comparing 4 with 16 m stem-height for $\delta^{13}C$; $r=0.90$ and $Glk=88\%$, comparing 4 with 12 m stem-height for $\delta^{18}O$; Fig. 4).

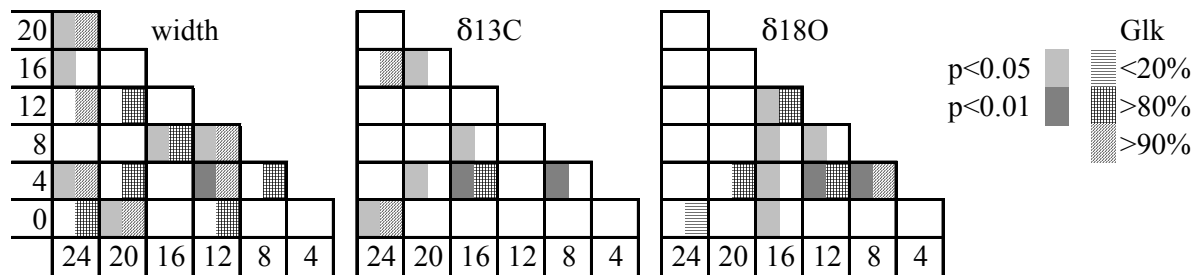


Figure 8: Simple correlations (light gray: $p < 0.05$; dark gray: $p < 0.01$; all positive) and Glk (horizontal lines: $< 20\%$, squared: $> 80\%$, striped: $> 90\%$) of latewood-widths (left), $-\delta^{13}C$ (middle) and $-\delta^{18}O$ (right) of 10 tree-rings ($n=10$) representing identical calendar years at seven tree heights. Numbers give the stem-height-level.

3.1.2 Identical cambial age

The variation of LW-width and -stable isotopic ratios with identical cambial age is shown in Figure 9.

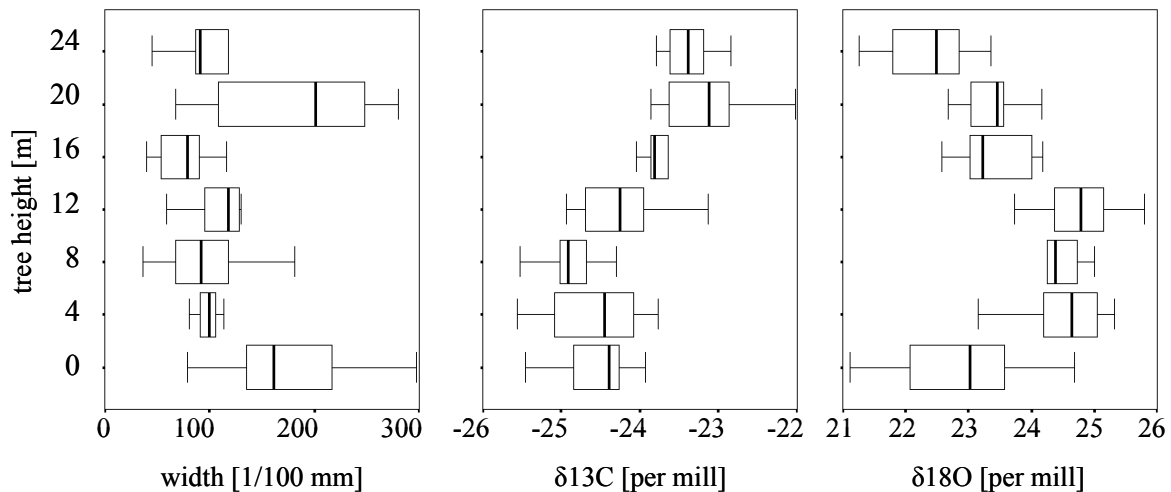


Figure 9: Box-whisker plots of LW-widths (left), $-\delta^{13}C$ (middle) and $-\delta^{18}O$ (right) from decadal samples covering 10 tree-rings ($n=10$) representing identical cambial ages at seven tree heights. Boxes indicate quartiles and include the median. Whiskers give the 1.5-times interquartile distance from the end of the box.

Values for widths show high variability with stem-height. Isotopic data both show a trend with stem-height: $\delta^{13}\text{C}$ increases and $\delta^{18}\text{O}$ decreases with stem-height.

Stem-height variation of widths and stable isotopic ratios, following the same cambial rings, revealed weaker statistical relationships than following identical calendar rings (Fig. 10). With longer time spans the few relationships might fade out.

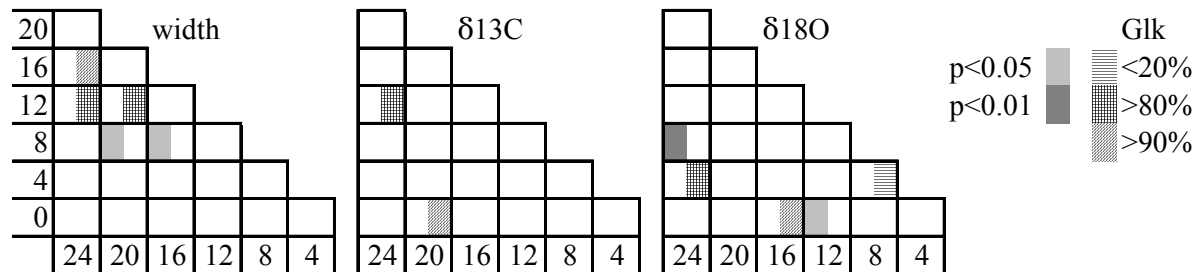


Figure 10: Simple correlations (light gray: $p < 0.05$; dark gray: $p < 0.01$; all positive) and Glk (horizontal lines: $< 20\%$, squared: $> 80\%$, striped: $> 90\%$) of LW-widths (left), $-\delta^{13}\text{C}$ (middle) and $-\delta^{18}\text{O}$ (right) of 10 tree-rings ($n=10$) representing identical cambial ages at seven tree heights. Numbers give the stem-height-level.

3.2 Radial variations

A plot of all twelve standardized time series is shown in Figure 11 with widths on the top, carbon isotopes in the middle and oxygen isotopes at the bottom. Series are shifted on the ordinate for better visualization of annual trends.

The LW, TR and TTR graphs for the widths and $\delta^{13}\text{C}$ are very similar, they show almost the same relative differences from one year to the next. $\delta^{18}\text{O}$ -values show much more variations between the tree-ring-sections.

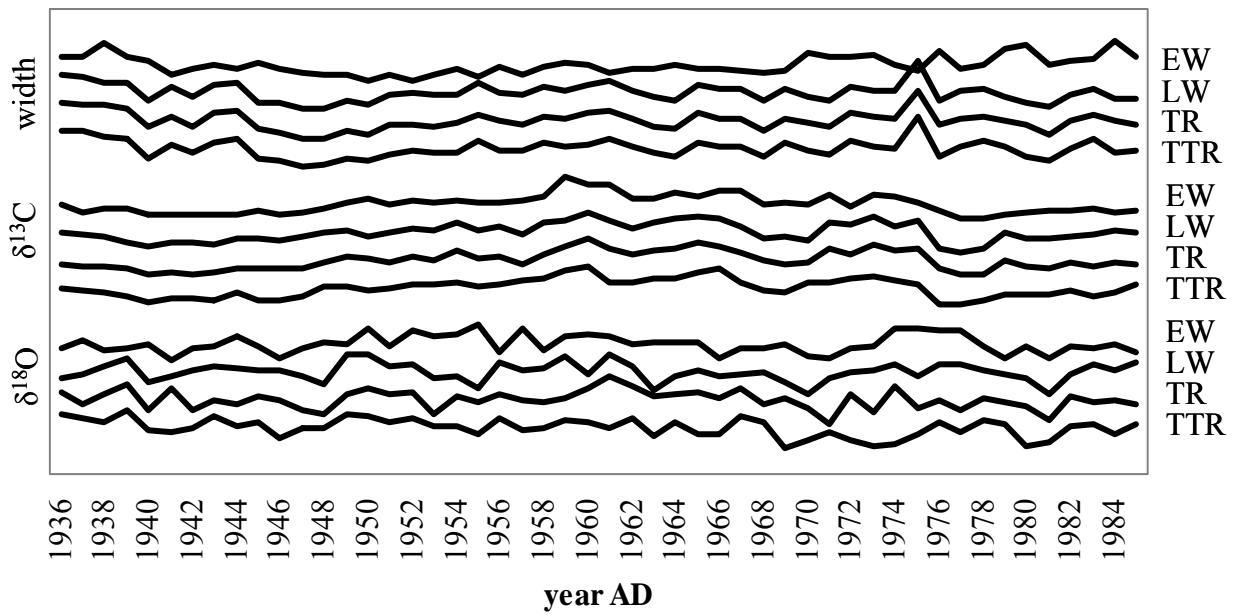


Figure 11: Width- (top), $\delta^{13}\text{C}$ - (middle) and $\delta^{18}\text{O}$ - (below) indices (z-transformed) for all four tree-ring-sections (EW, LW, TR and TTR).

3.2.1 Relations along and between the tree-ring-parameter (widths and stable isotopes)

The significant autocorrelations (first, second and third order) of raw data for all three tree-ring-parameter (width, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) and for all four tree-ring-sections can be seen in Table 2. Further, the average mean sensitivities of standardized values are shown.

Table 2: First, second and third order autocorrelation of raw data and mean sensitivity of standardized (z-transformed) EW-, LW-, TR- and TTR- widths, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values (n=50). Light gray indicates significant ($p < 0.05$) and dark gray highly significant autocorrelation ($p < 0.01$).

		AC (1)	AC (2)	AC (3)	mean sensitivity
Width	EW	0.536	0.374	0.331	1.095
	LW	0.286	0.182	0.169	1.205
	TR	0.412	0.266	0.202	1.239
	TTR	0.292	0.181	0.208	1.217
$\delta^{13}\text{C}$	EW	0.783	0.657	0.484	0.781
	LW	0.670	0.476	0.205	0.954
	TR	0.752	0.573	0.348	0.878
	TTR	0.790	0.560	0.409	0.712
$\delta^{18}\text{O}$	EW	0.297	0.343	0.046	1.253
	LW	0.210	-0.064	-0.087	1.333
	TR	0.025	0.258	-0.128	1.541
	TTR	0.332	0.118	0.160	1.302

The values of Glk and TVBP as well as for simple and partial correlation are illustrated in Figure 12. Just significant ($p < 0.05$) and highly significant ($p < 0.01$) values for Glk, simple and partial correlation and TVBP higher than 4.0 respective 13 are shown.

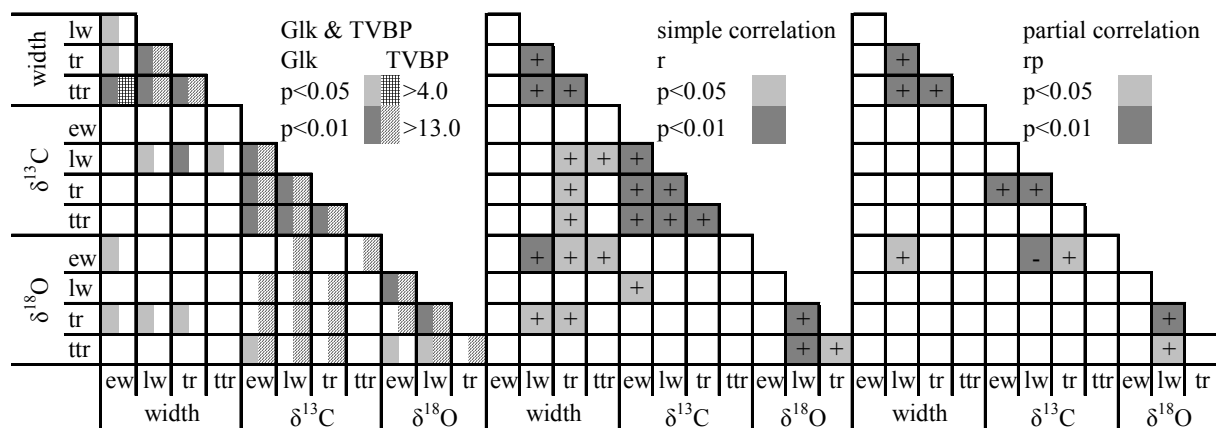


Figure 12: Glk (light gray: $p < 0.05$, i.e. $> 62\%$; dark gray: $p < 0.01$, i.e. $> 67\%$) and TVBP (squared: > 4 ; striped: > 13), simple and partial correlation (light gray: $p < 0.05$; dark gray: $p < 0.01$) of standardized widths, $\delta^{13}\text{C}$ - and $\delta^{18}\text{O}$ -values (n=50). Signs indicate pos. (+) and neg. (-) values for r respective r_p .

3.2.2 Climate-growth relationships

All significant simple correlations of the 12 standardized tree-ring parameters with the three climatic parameters (temperature, precipitation, GNIP-data) for the time span from previous September to current September are given in the Figures 13 (widths), 14 ($\delta^{13}\text{C}$) and 15 ($\delta^{18}\text{O}$).

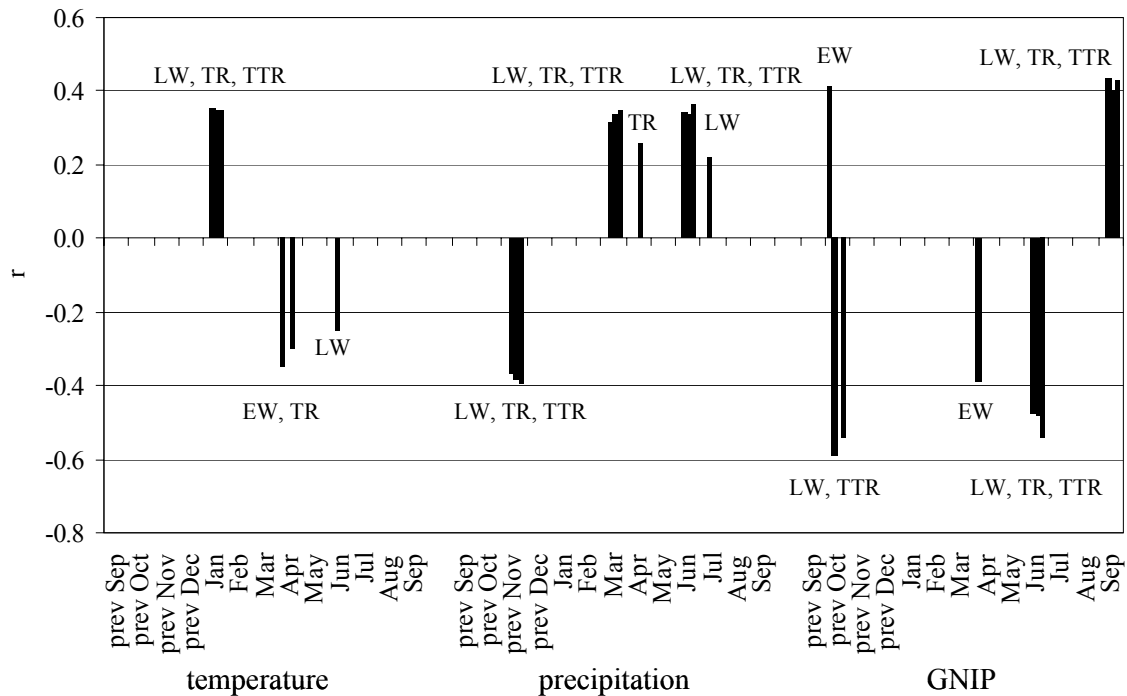


Figure 13: Significant simple correlations (r , $p < 0.05$) of width-indices with temperature ($n=50$), precipitation ($n=50$) and GNIP-data ($n=25$), each from previous September to current September.

The width-parameter showed six significant simple correlations with three different monthly temperatures (January, April and June), eleven with five different monthly precipitation amounts (previous November, March, April, June and July) and ten with four different monthly $\delta^{18}\text{O}$ -values of precipitation (GNIP) (previous October, April, June and September).

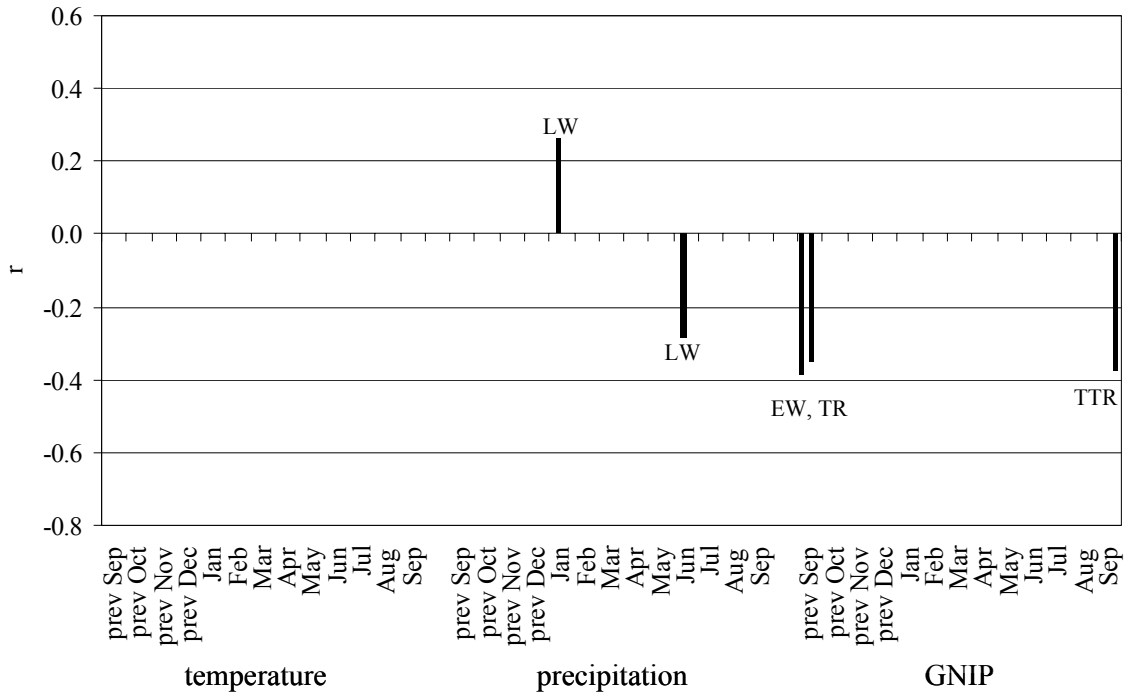


Figure 14: Significant simple correlations (r , $p < 0.05$) of $\delta^{13}\text{C}$ -indices with temperature ($n=50$), precipitation ($n=50$) and GNIP-data ($n=25$), each from previous September to current September.

There was no significant correlation between $\delta^{13}\text{C}$ -values and temperature of any month tested. Two significant correlations of $\delta^{13}\text{C}$ were found with precipitation amount of January and June and three could be found with GNIP-data of previous September and current September.

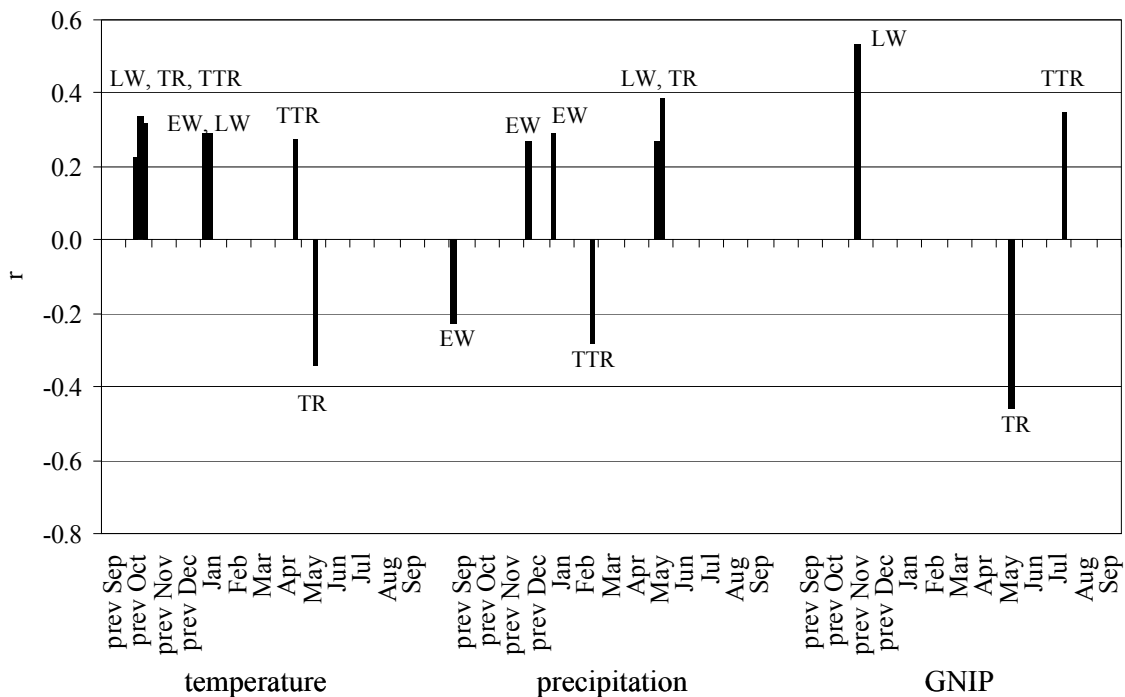


Figure 15: Significant simple correlations (r , $p < 0.05$) of $\delta^{18}\text{O}$ -indices with temperature ($n=50$), precipitation ($n=50$) and GNIP-data ($n=25$), each from previous September to current September.

$\delta^{18}\text{O}$ -values showed seven significant simple correlations in four different months with temperature (previous October, January, April and May), six in five different months with precipitation amount (previous September, previous December, January, February, and May) and three in three different months with GNIP-data (previous November, May and July).

4 Discussion

Stem height profiles of widths showed a range of about 0.5 mm for samples of identical calendar years and of about 1 mm for samples of identical cambial years. Range for all isotope values was slightly higher than 1.5 ‰.

Increasing values with stem height could be found for $\delta^{13}\text{C}$ -values of identical cambial age and decreasing values for $\delta^{18}\text{O}$ -values of both identical calendar year and cambial year. A tendency to lower values in the middle of the trunk and higher once at the bottom and the top of the trunk could be found for widths and $\delta^{13}\text{C}$ -values of identical calendar year. Width-values of identical cambial age showed strong variability with stem height.

Stem-height variation of widths and stable isotopic ratios revealed weaker statistical relationships for samples of identical cambial years than following identical calendar years.

Low autocorrelations could be found for $\delta^{18}\text{O}$ -values and for the widths. The statistical relationships within the parameter (widths, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) turned out to be very strong and much poorer between the parameter.

A number of significant correlations between ring-widths respectively $\delta^{18}\text{O}$ -values and climatic parameter (temperature, precipitation and GNIP-data) could be found for the period from previous to current year September.

4.1 Axial variations

Samples taken from 24m height belonging to the crown might be affected by species specific branch and shoot characteristics. Roloff (2001) reports that *Quercus petraea* tends to form very long shoots, summer shoots, reiterations and often shoots from sleeping buds.

4.1.1 Identical calendar year

The total variation of $\delta^{13}\text{C}$ is higher than the one found by Schleser (1992), who reported a variation of less than 1.5‰ along the trunk of a beech tree with the radial direction kept constant. The additional variability found here may be either caused by the species or by the random selection of radial directions, due to the circumferential variation of $\delta^{13}\text{C}$ -values of up to 4‰ (Tans & Mook 1980; Leavitt & Long 1986; Schleser 1999). The $\delta^{13}\text{C}$ -pattern shows a quite similar slope to the trends in latewood-widths. In contrast, no significant height-dependant trends were found by Schleser (1992).

The relations along the stem-height for identical calendar year are the strongest for LW-width and the weakest for LW- $\delta^{13}\text{C}$. Maybe if all samples would have been taken from the same side of the trunk even strong relations for LW- $\delta^{13}\text{C}$ could have been found. It should also be kept in mind that samples covered just 10 tree-rings. With a longer time span for sure spurious associations could also be filtered out.

4.1.2 Identical cambial age

The variability of LW-width with stem-height is higher than for samples of identical calendar years. $\delta^{13}\text{C}$ -values reveal a distinct shift of roughly 1.5‰ from more negative values at the bottom to less negative values at the top of the stem. This trend especially could be seen after correcting the LW- $\delta^{13}\text{C}$ -values according to the decreasing $\delta^{13}\text{C}$ -values of the atmospheric CO_2 source.

When the value at 0 m is not considered, LW- $\delta^{18}\text{O}$ -values of identical cambial ages also show a trend with stem-height that is stronger than the one reported for identical calendar years. However, the trend with stem-height of LW- $\delta^{18}\text{O}$ -values follows the opposite direction to the one seen with the $\delta^{13}\text{C}$ -values, i.e. from higher values at 4 m height to lower values at 24 m.

According to Scheidegger et al. (2000), trends of both stable isotopes point to increasing photosynthetic rates at constant stomatal conductivity caused by increasing air temperatures at a constant humidity and water supply.

All these trends and the low amount of significant correlations, together with significant Glk-values indicate a much higher influence of calendar year than of cambial age. This means that exterior factors like climatic conditions have a stronger impact than internal factors (i.e. cambial age).

4.2 Radial variations

The strong similarities in the width-measurements of LW, TR and TTR show clearly that radial growth was dominated by LW-growth. Similarities between stable isotopes are much weaker than for widths. This indicates that the influencing factors on isotopic values of each tree-ring-section are more different than for the widths. Just a few really characteristic similarities could be found for stable isotopes (e.g. 1975 to 1979 for LW-, TR- and TTR- $\delta^{13}\text{C}$ or 1949 to 1958 for LW- and TTR- $\delta^{18}\text{O}$).

Autocorrelations calculated for raw data from all three tree-ring parameter (width, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) showed different results for all four tree-ring sections. $\delta^{13}\text{C}$ showed highest significant first and

second order autocorrelations, no matter of the regarded tree-ring section. Even third order autocorrelations were significant or highly significant, except for LW $\delta^{13}\text{C}$.

In contrast, only EW $\delta^{18}\text{O}$ (first and second order) and TTR $\delta^{18}\text{O}$ (first order) revealed significant autocorrelations.

All widths measurements showed significant or highly significant first order autocorrelations. However, only EWW showed significant autocorrelation of second and third order. Generally, autocorrelations for ring-widths were lower than described by Weigl et al. (2004).

On one hand, this gives some indication of the limitations of single stem analysis, on the other hand, the good overall agreement confirms the validity of the approach in this study. Due to their annual resolution, precise dating and spatial coverage, tree-ring records from living, dead and fossil wood are invaluable proxy sources for well-replicated environmental or climate reconstructions of the past 10,000 years. Finding tree-ring parameters showing low autocorrelations is of great interest for reconstructions of climate variability. In this respect, $\delta^{18}\text{O}$ -values and to a little lesser extent width-values would fulfill this criterion.

The reason for the high autocorrelation of $\delta^{13}\text{C}$ -values found here may be explained from the tri-phase high resolution pattern of $\delta^{13}\text{C}$ reported by Helle and Schleser (2004) for tree-rings of broadleaf trees. It starts with increasing values from a high level up to the annual maximum within the EW, followed by declining values reaching the annual minimum within the LW and once again increasing values towards the very end of the LW. This pattern is attributed to the use of reserve substances at the beginning and the very end of a vegetation period in contrast to the incorporation of current year assimilates in between. As the pattern shows gradual changes from high values during EW development to low values in the LW, the value at the maximum of the year t depends on the value of the minimum of the year $(t-1)$ and later depends on the value of the maximum of the year $(t-1)$. In this respect also series of maxima (EW $\delta^{13}\text{C}$) or minima (LW $\delta^{13}\text{C}$) can easily be autocorrelated.

Mean sensitivity of raw ring width data of the investigated tree are comparable with the site data described by Weigl et al. (2004). Taking into account that standard deviation of isotopic values is much smaller than the one of widths, comparison of mean sensitivity of these parameter was only possible after standardization. Oxygen turned out to be most sensitive closely followed by the widths. Carbon was found to be remarkably less sensitive.

The findings for mean sensitivity fit quite well with the climatic correlations. Mean sensitivity of LWW, TRW and TTRW is very similar. Significant correlations could often be found with all three measurements for the same climatic variable (i.e. January temperature, previous November, March and June precipitation, June and September GNIP-data). EWW is not as sensitive as LWW, TRW and TTRW, which results in a reduced number of significant correlations with climatic variables for the investigated time period (EWW: 3, LWW: 9, TRW: 8 and TTRW: 7).

Although oxygen shows the highest mean sensitivity less significant correlations to climatic variables compared to the widths could be found maybe due to selection of climatic variables. $\text{TR}\delta^{18}\text{O}$ shows the highest mean sensitivity. Among all oxygen-data $\text{TR}\delta^{18}\text{O}$ revealed the highest negative correlation values.

The comparably low mean sensitivity of $\delta^{13}\text{C}$ is also visible in the low amount of, and even low values, for significant correlations with climatic variables. $\text{LW}\delta^{13}\text{C}$ that is the most sensitive one among all $\delta^{13}\text{C}$ -values, shows two significant correlations while all the others just show one.

Analyses of Glk and TVBP revealed strong relationships for each tree-ring parameter measured in different tree ring sections (e.g. $\text{Glk}=96\%$ and $\text{TVBP}=38.8$ for LWW vs. TTRW, $\text{Glk}=84\%$ and $\text{TVBP}=41.5$ for $\text{LW}\delta^{13}\text{C}$ vs. $\text{TR}\delta^{13}\text{C}$ or $\text{TVBP}=19.1$ for $\text{LW}\delta^{18}\text{O}$ vs. $\text{TR}\delta^{18}\text{O}$).

Also a number of matchings between the different parameters could be found in Glk and TVBP. $\text{TR}\delta^{18}\text{O}$ -values showed good agreement in Glk with EWW, LWW and TRW, but not with TTRW. TVBP revealed relationships between $\delta^{13}\text{C}$ - and $\delta^{18}\text{O}$ -values of most of the different tree ring sections. Interestingly, $\text{EW}\delta^{18}\text{O}$ and $\text{EW}\delta^{13}\text{C}$ show no relationship at all in any of the statistical parameters shown in Figure 8. Both isotopes measured in the TTR showed any relationship with width of any tree-ring section. Not even TTRW was related to $\text{TTR}\delta^{13}\text{C}$ or $\text{TTR}\delta^{18}\text{O}$.

Simple correlation analysis showed weak ($p<0.05$) but significant positive associations between $\text{TTR}\delta^{13}\text{C}$ and TRW, as well as between TTRW and $\text{EW}\delta^{18}\text{O}$. Since these relationships cannot be seen in Glk or TVBP this may be related to similarities in lower frequencies and not in high frequency year to year changes. Further more no physiological explanation could be found why TVBP showed good matching of $\text{EW}\delta^{18}\text{O}$ with $\text{TTR}\delta^{13}\text{C}$ ($\text{TVBP}=18.1$).

Some pairs of parameters showed significant partial correlations and TVBP-values from 4.0 up to 41.5 (e.g. pairs of LW-, TR- and TTR-width), while other pairs showed TVBP-values in a similar range (4.4 - 43.3) but no significant partial correlations (e.g. almost all pairs of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$).

In general results for Glk and TVBP can not be seen as comparable with the once for simple and partial correlation. For example significant Glk could be found between parameters (width, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) that can not be supported by significant simple or partial correlation. Also matching between $\delta^{13}\text{C}$ - and $\delta^{18}\text{O}$ -values seems to be much stronger using TVBP instead of simple or partial correlations. The conflicts in comparing Glk and TVBP with simple and partial correlation can be attributed to the highly specification of Glk and TVBP on width-parameter. Obviously they can not be easily used for other types of time-series (e.g. isotope records).

In comparison to the data of TVBP, simple correlations showed some contrasting results. While, once again, strong relationships within each group of parameters could be found (e.g. LWW vs. TRW $r=0.979$, LW $\delta^{13}\text{C}$ vs. TR $\delta^{13}\text{C}$ $r=0.912$ or LW $\delta^{18}\text{O}$ vs. TR $\delta^{18}\text{O}$ $r=0.555$), most of the simple correlations between $\delta^{13}\text{C}$ - and $\delta^{18}\text{O}$ -values were not significant. Significant simple correlations could be found between widths and both stable isotopes (e.g. TRW vs. TR $\delta^{13}\text{C}$ $r=0.328$ or LWW vs. EW $\delta^{18}\text{O}$ $r=0.365$).

Comparing the same tree-ring-parameters from different tree-ring-sections, values from EW and TTR showed no significant correlations. In LW both isotopes correlated significantly, and TR showed significant simple correlations between widths and both isotopes. No significant simple correlations with any other parameter from the different tree-ring-sections could be found for EWW, which supported the above results (low TVBP, no significant partial correlations).

The results of simple correlation were validated by the use of partial correlations (r_p). Compared to simple correlation analyses the amount of significant correlations along the parameter (width, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$) decreased (from 12 to 7 out of 18 pairs) and also most of the significant correlations between the parameter disappeared (from 10 to 3 out of 48 pairs). This means that all the significant and some of the highly significant simple correlations were just indirect relationships (e.g.: TRW vs. several $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ -values or TR $\delta^{13}\text{C}$ vs. TTR $\delta^{13}\text{C}$). On one hand, all significant or highly significant partial correlations showed lower r_p - than r -values calculated for simple correlation (e.g. LWW vs. TRW $r_p=0.972$ [-0.007], LW $\delta^{13}\text{C}$ vs. TR $\delta^{13}\text{C}$ $r_p=0.783$ [-0.129], LW $\delta^{18}\text{O}$ vs. TR $\delta^{18}\text{O}$ $r_p=0.391$ [-0.164]). On the other hand, two significant partial correlations appeared that were not

significant using simple correlations (LW $\delta^{13}\text{C}$ vs. EW $\delta^{18}\text{O}$ $r_p=-0.403$ [highly significant], TR $\delta^{13}\text{C}$ vs. EW $\delta^{18}\text{O}$ $r_p=0.382$ [significant]).

Obviously no significant partial correlations could be found between the parameters within the same tree-ring-sections. In addition, the strong relations between $\delta^{13}\text{C}$ - and $\delta^{18}\text{O}$ -values like described by TVBP could not be found using partial correlations, which could be attributed to similarities in lower frequency than year to year-variations.

Since Barbaroux and Bréda (2002) showed that the growing season of oak starts roughly 10 days before bud break (usually middle of April) and ends at the end of summer (usually end of September), the most significant period was expected to be the time from April to September. The high number of significant correlations are scattered all over the time span from previous September to current September, while they are the weakest for the current summer months. So this assumption can not be supported.

Generally, it turned out that the highest correlations to climate could be found for GNIP-data, but the GNIP-data covered just 25 instead of 50 years (like for temperature and precipitation). A reduction of the time span to 25 years (1961 to 1985) for the other climatic parameter would for example increase the correlation of TTR $\delta^{18}\text{O}$ with previous October temperature from 0.321 to 0.611. In this respect correlations with GNIP-data appeared to be overrated.

Significant simple correlations that just could be found with widths were with June temperature, with previous November, March, April and July precipitation amount and with previous October, April and June GNIP-data.

Although widths show the most significant simple correlations with climate, a lot of additional significant simple correlations could be found for stable isotopes (especially $\delta^{18}\text{O}$). Significant simple correlations with previous October and May-temperature, with previous September, previous December, January, February and May-precipitation and with previous November, May and July-GNIP could just be found for $\delta^{18}\text{O}$. Significant simple correlations with January precipitation and with previous September GNIP-data just could be found for $\delta^{13}\text{C}$. For none of the climatic parameters significant simple correlations could be found for all the three parameter (width, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$).

Values for r were always higher for width-parameter than for stable isotopes (January and April temperature, June precipitation and September GNIP), and in the case of January precipitation the correlation with $\delta^{18}\text{O}$ (EW) is higher than the one with $\delta^{13}\text{C}$ (LW). The highest significant simple correlations of $\delta^{18}\text{O}$ -values could be found with TR.

Concerning the width-data, TR always gave the lowest significant values. The highest significant simple correlation within the widths could be found for TTRW with precipitation (previous November).

Comparing results for precipitation and GNIP-data it gets obvious that just a few similar results could be found. Ring-widths (LW, TR and TTR) showed significant simple correlations of about $r_{\text{prec}}=0.35$ with June-precipitation and about $r_{\text{GNIP}}=-0.5$ with June-GNIP, and $\text{TR}\delta^{18}\text{O}$ with May-precipitation ($r_{\text{prec}}=0.385$) and with May-GNIP ($r_{\text{GNIP}}=-0.461$). The fact that just these few results could be found for identical months is not surprising as the influence of precipitation amount had been taken out of the GNIP-data.

Comparison of significant simple correlations found with temperature and GNIP-data showed similar values for r in April (EWW: $r_{\text{temp}}=-0.349$, $r_{\text{GNIP}}=-0.389$), May ($\text{TR}\delta^{18}\text{O}$: $r_{\text{temp}}=-0.342$, $r_{\text{GNIP}}=-0.461$) and June (LWW: $r_{\text{temp}}=-0.250$, $r_{\text{GNIP}}=-0.461$). Rozanski et al. (1992) calculated a correlation showing the dependency of the long-term changes in GNIP-data on the long-term changes in temperature for Vienna with $r=0.6$. In this respect it is not surprising that significant correlations with identical months could be found within a climate-proxy-data source (i.e. this tree) for temperature- and GNIP-data.

The interesting thing about it is that comparison of significant simple correlations found with all three climatic parameter showed that just May ($\text{TR}\delta^{18}\text{O}$) and June (LWW) could be found. Although these results just represent a single tree, climatic conditions in these two months really seem to be of big importance for radial tree growth of oak at this site. Similar results for June - temperature and -precipitation can also be found in Eilmann (2004) for LWW.

The huge number of significant simple correlations of width-parameter and $\delta^{18}\text{O}$ -values to climatic parameter showed the great potential of these two climate proxies. The lowest amount of significant simple correlations, and also low r -values, could be found for $\delta^{13}\text{C}$ -values.

No significant simple correlations could be found for eight months with temperature (previous September, previous November, previous December, February, March, July, August and September), three months with precipitation (previous October, August and September) and five months with GNIP-data (previous December, January, February, March and August). The August climate parameters showed no significant simple correlation to any data-set.

Significant simple correlations of LWW and TRW with temperature and precipitation are similar to earlier findings. Positive simple correlations of TRW with January temperature were described by Eckstein and Schmidt (1974). Brockmann et al. (1987) even found negative simple correlations for TRW with April temperature and positive simple correlations with March precipitation (also in Becker & Glaser 1991), April precipitation (also in Krause 1992) and June precipitation (also in Pilcher & Gray 1982). Negative simple correlations of LWW with June temperature (Eilmann 2004) and positive simple correlations with March precipitation (Krause 1992) and June precipitation (Krause 1992; Eilmann 2004) can also be found in literature. The significant negative simple correlation of EWW with April-GNIP-data ($r=-0.389$) could be explained by the influence of melting snow on the isotopic composition of soil water. Treydte et al. (2005) found a highly significant correlation for the total $\delta^{18}\text{O}$ -network produced within the project ISONET with temperature of the time span from April to September. These findings can partly be supported as $\text{TTR}\delta^{18}\text{O}$ shows significant correlation with April temperature and $\text{TR}\delta^{18}\text{O}$ with May temperature. For example no explanation for simple correlations of widths with previous November precipitation could be found.

5 Conclusion

Cambial age has only little effect on the axial variations of LW-widths and -stable isotopes, so that hypotheses number 3 needs to get rejected. Formation of “adult heartwood” is mostly driven by external environmental factors. The isotopic trends observed for identical cambial ages are likely due to the long term climatic changes since the late 19th century. Increasing $\delta^{13}\text{C}$ -values in conjunction with decreasing $\delta^{18}\text{O}$ -values can be explained by increasing photosynthetic rates.

The influence of stem-height on the measured parameters of the same calendar years seems to be limited so that samples taken from historical wood, without any a priori knowledge about within-stem position, can be also utilized. This means that hypotheses number 2 and 4 can be accepted and hypotheses number 1 needs to be rejected. Although restrictions to one radial direction per wood sample often exist, a second direction on the same wood sample would probably reduce the variability of stable isotopic values.

In many cases some of the twelve different tree-ring-values show comparable results concerning there simple correlation with climate. The strongest simple correlations with climate were seen at TTR for the widths (previous November precipitation), LW for $\delta^{13}\text{C}$ (June precipitation) and TR for $\delta^{18}\text{O}$ (May precipitation). Also high mean sensitivity of $\delta^{18}\text{O}$ -values and widths and low autocorrelations of $\delta^{18}\text{O}$ indicate the good usability of these parameters in climatic studies.

The poor results for $\delta^{13}\text{C}$ compared to the huge amount of significant simple correlations found for widths and $\delta^{18}\text{O}$ assume that measurements on cellulose might have been more successful. On the other hand, this single tree dose not represent the whole site. Many other publications show a good potential of $\delta^{13}\text{C}$ -values for climate reconstruction (e.g. Treydte 2002; Helle & Schleser 2004; Treydte et al. 2004).

Usage of LW for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ is a compromise that is often done. Further investigations should show whether good results can be found with TR-cellulose for $\delta^{13}\text{C}$. This would reduce the amount of practical work, as TR-wood could be used for $\delta^{18}\text{O}$ and additionally if necessary TR-cellulose for $\delta^{13}\text{C}$.

Zhang (1997) showed the relationships between climate and EW-, LW- and TR- width and density and pointed out the unique potential of each parameter as a climatic proxy. Strong relationships

along the parameter (width, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$) used in this study were seen, while the relationships between the parameter are weak. Also here, these different potentials of parameter can be seen.

Summarizing hypotheses number 5 can be accepted concerning the relations within the parameter and must be rejected concerning the relations between the parameter. Hypotheses number 6 can be accepted.

To get good results for climatic studies, it is more important to choose the best suited parameter (width, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$) rather than working with different tree-ring-sections (EW, LW, TR, TTR). More information can be extracted by the use of several parameters than by the use of different tree-ring-section for the same parameter. From a practical point of view it should be pointed out that it is quicker and cheaper to do width-measurements with intra-annual resolution previously and to decide about isotopic measurements later on.

6 Summary

A single sessile oak tree (*Quercus petraea* (Matt.) Liebl.) from the Lainzer Tiergarten was selected to analyse the variability of ring-widths and stable isotopes ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) deposited in tree-rings. Furthermore, the meaning of these analyses to reconstruct climate is also demonstrated.

Axial variation of latewood-widths and stable isotopes in latewood as well as the radial variation of widths and stable isotopes present in different tree-ring-sections of the tree, were analyzed. To analyze the radial variations tree-rings were separated into early- and latewood, complete tree-ring and so called transfer tree-ring, the latter being the latewood plus the earlywood of the subsequent year.

The influence of sampling height was found to be weak for both latewood-widths and stable isotopes measured in latewood. The observed trends with stem-height show clearly that possible effects due to cambial aging are overrated by annual effects. In addition, relations between samples from different stem-heights are strong for identical calendar years while they are poor for identical cambial age. All this indicates that samples from both, living trees and historical wood can be taken from any height position of a trunk or beam as long they are free from anatomical abnormalities.

Concerning radial variations, widths and $\delta^{18}\text{O}$ -values showed low autocorrelation while most of the tree-ring parameters showed highly significant autocorrelations of higher order for $\delta^{13}\text{C}$. Mean sensitivity of standardized values was in the range of 1.095 to 1.239 for widths and 0.712 to 0.954 for $\delta^{13}\text{C}$ and 1.253 to 1.541 for $\delta^{18}\text{O}$. Other statistical parameters showed that relations along the parameter (width, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$) are much stronger than between different parameter. This indicates a unique potential of each parameter for climate reconstruction.

Correlation with temperature, precipitation and oxygen isotopes in precipitation, i.e. GNIP-data, showed extraordinary high potentials of latewood-, tree-ring- and transfer tree-ring-widths and - $\delta^{18}\text{O}$ for climate reconstruction. The best results along each of the three methods could be found for transfer tree-ring-width, latewood- $\delta^{13}\text{C}$ and tree-ring- $\delta^{18}\text{O}$. For climatic studies, the selection of the best parameter (width, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$) gives more different results than the selection of different tree-ring sections (EW, LW, TR, TTR) using just one parameter.

7 Zusammenfassung

Eine Flaumeiche (*Quercus petraea* (Matt.) Liebl.) vom Standort Lainzer Tiergarten wurde einer Ganzstammanalyse unterzogen. Ziel der Analyse war es, die Variationen von Jahrringbreiten und von in den Jahrringen gespeicherten stabilen Isotopen ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) zu analysieren und ihre Bedeutung für die Klimarekonstruktion darzustellen.

Die Variationen der Spätholzbreiten und stabilen Isotope im Spätholz sowie radiale Variationen von Jahrringbreiten und in den Jahrringen gespeicherten stabilen Isotopen wurden entlang des Stamms untersucht. Für die Analyse der radialen Variationen wurden die Jahrringe in Früh- und Spätholz, Jahrring und Transfer-Jahrring (Spätholz plus Frühholz des folgenden Jahres) unterteilt.

Sowohl für die Spätholzbreiten als auch die stabilen Isotope im Spätholz wurde nur eine geringe Abhängigkeit von der Stammhöhe festgestellt. Die Verläufe mit der Stammhöhe zeigen deutlich, dass ein möglicher Einfluss des Kambialalters von klimatischen Signalen überschattet wird. Darüber hinaus sind die Beziehungen zwischen Messdaten aus unterschiedlicher Stammhöhe für Proben mit gleichem Kalenderjahresbezug stark ausgebildet, während die Beziehungen für Proben identischen Kambialalters schwach sind. Die Ergebnisse zeigen, dass Proben grundsätzlich aus jeder beliebigen Höhe sowohl von lebenden Bäumen als auch von historischem Holz entnommen werden können, solange keine anatomischen Abnormitäten vorliegen.

Die radialen Variationen der Breiten und der $\delta^{18}\text{O}$ -Werte zeigten niedrige Autokorrelation. Im Gegensatz dazu zeigten die meisten Jahrring-Elemente für die $\delta^{13}\text{C}$ -Werte hoch signifikante Autokorrelationen. Nach Standardisierung lag die mittlere Sensitivität der Jahrringbreiten im Bereich von 1.095 bis 1.239, für $\delta^{13}\text{C}$ zwischen 0.712 und 0.954 und für $\delta^{18}\text{O}$ zwischen 1.253 und 1.541. Gleichläufigkeit, einfache und partielle Korrelation zeigten, dass die Beziehungen innerhalb der Parameter (Breite, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$) stärker sind als zwischen den Parametern. Das deutet darauf hin, dass jeder Jahrring-Parameter ein einzigartiges Potential zur Klimarekonstruktion hat.

Korrelationen mit Temperatur, Niederschlag und Sauerstoffisotopen im Niederschlag (GNIP-Daten) zeigten ein besonders hohes Potential für Spätholz-, Jahrring- und Transferjahrring-Breiten und - $\delta^{18}\text{O}$ für die Klimarekonstruktion auf. Die besten Ergebnisse innerhalb der drei Parameter zeigten sich für Transferjahrringbreiten, Spätholz- $\delta^{13}\text{C}$ und Jahrring- $\delta^{18}\text{O}$. Die Auswahl des besten Parameters (Breite, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$) ergibt mehr klimatisch verwertbare Ergebnisse als die Auswahl

verschiedener Jahrringelemente (EW, LW, TR, TTR) die mit dem gleichen Parameter untersucht werden.

References

- Baillie, M.G.L. & J.R. Pilcher. 1973. A simple cross-dating program for tree-ring research. *Tree-Ring Bulletin* 33: 7-14.
- Baillie, M.G.L. 1995. *A Slice Through Time: Dendrochronology and Precision Dating*. B.T. Batsford, London.
- Barbaroux, C. & N. Bréda. 2002. Contrasting distribution and seasonal dynamics of carbohydrate reserves in stem wood of adult ring-porous sessile oak and diffuse-porous beech trees. *Tree Physiology* 22: 1201-1210.
- Becker, B. & R. Glaser. 1991. Baumringsignaturen und Wetteranomalien (Eichenbestand Guttenberger Forst, Klimastation Würzburg). *Forstwissenschaftliches Centralblatt* 110: 66-83.
- Biondi, F. & K. Waikul. 2004. DENDROCLIM2002: A C++ program for statistical calibration of climate signals in tree-ring chronologies. *Computers & Geosciences* 30: 303-311.
- Borella, S., M. Leuenberger, M. Saurer & R. Siegwolf. 1998. Reducing uncertainties in $\delta^{13}\text{C}$ analysis of tree rings: Pooling, milling and cellulose extraction. *Journal of geophysical research* 103: 19519-19526.
- Bosshard HH. 1974. *Holzkunde, Band 2. Zur Biologie, Physik und Chemie des Holzes*. Basel: Birkhäuser Verlag.
- Brenninkmeijer, C.A.M. 1983. *Deuterium, oxygen-18 and carbon-13 in tree rings and peat deposits in relation to climate*. University of Groningen, 1st edition.
- Brockmann, W.G., D. Eckstein & R.W. Aniol. 1987. Dendroklimatologische Untersuchungen zur Bedeutung des Produktionsfaktors Wasser für das Baumwachstum. *Forstwissenschaftliches Centralblatt* 106: 340-354.
- Cherubini, P., H. Gärtner, J. Esper, M.K. Dobbertin, K.F. Kaiser, A. Rigling, K. Treydte, N.E. Zimmermann & O.U. Bräcker. 2004. Jahrringe als Archive für interdisziplinäre Umweltforschung. *Schweizerische Zeitschrift für Forstwesen* 155(6): 162-168.
- Cook, E.R. & L.A. Kairiukstis. 1990. *Methods of dendrochronology: applications in the environmental science*. Kluwer academic publishers, Dordrecht.
- Cook, E. & P.J. Krusic. 2005. Program ARSTAN. A Tree-Ring Standardization Program Based on Detrending and Autoregressive Time Series Modelling, with Interactive Graphics.
- Craig, H. & L.I. Gordon. 1965. Deuterium and oxygen-18 variations in the ocean and the marine atmosphere. In: Tongiorgi, S. (ed.): *Stable isotopes in oceanographic studies and paleotemperatures*. Spoleto Conferences in Nuclear Geology, Paris: 9-130.

- Dongmann, G., H.W. Nürnberg, H. Förstel & K. Wagener. 1974. On the enrichment of H₂¹⁸O in leafs of transpiring plants. *Radiation and Environmental Biophysics* 11: 41-52.
- Eckstein, D. & J. Bauch. 1969. Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens und zur Analyse seiner Aussagesicherheit. *Forstwissenschaftliches Centralblatt* 88: 230-250.
- Eckstein, D. & B. Schmidt. 1974. Dendroklimatologische Untersuchungen an Stieleichen aus dem maritimen Klimagebiet Schleswig-Holsteins. *Angewandte Botanik* 48: 371-383.
- Eilmann, B. 2004. Wachstumsreaktion der Waldföhre (*Pinus sylvestris* L.) und der Flaumeiche (*Quercus pubescens* Willd.) auf klimatische Extremjahre – eine holzanatomische Studie. Masterthesen, University of Hamburg.
- Eilmann, B., P. Weber, A. Rigling & D. Eckstein. 2006. Growth reactions of *Pinus sylvestris* L. and *Quercus pubescens* Willd. To drought years at a xeric site in Valais, Switzerland. *Dendrochronologia* 23(3):1 21-32.
- Farquhar, G.D., M.H. O'Lary & J.A. Berry. 1982. On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. *Australian Journal of Plant Physiology* 9: 121-137.
- Farquhar, G.D., J.R. Ehleringer & K.T. Hubick. 1989. Carbon isotope discrimination and photosynthesis. *Annual Review of Plant Physiology and Plant Molecular Biology* 40: 503-537.
- Förstl, H. 1978. The enrichment of ¹⁸O in leaf water under natural conditions. *Radiation and Environmental Biophysics* 15: 323-344.
- Francey, R.J., C.E. Allison, D.M. Etheridge, C.M. Trudinger, I.G. Enting, M. Leuenberger, R.L. Langenfelds, E. Michel, L.P. Steele, M. Apps, F. Joos, D. Shimmel & A. Watson. 1999. A 1000-year high precision record of delta d13C in atmospheric CO₂. *Tellus, Series B: Chemical and Physical Meteorology* 51B(2): 170-193.
- Fritts, H.C. 1976. *Tree Rings and Climate*. London: Academic Press.
- García González, I. & D. Eckstein. 2003. Climatic signal of earlywood vessels of oak on a maritime site. *Tree Physiology* 23: 497-504.
- Geihofer, D., M. Grabner, J. Gelhart, R. Wimmer & H. Fuchsberger. 2005. New master chronologies from historical and archaeological timber in Eastern Austria. In: Sarlatto, M., A. Di Filippo, G. Piovesan & M. Romagnoli (ed.), *Eurodendro 2005, International Conference of Dendrochronology*, University of Tuscia: 50-51.
- Grabner, M. & R. Wimmer. 2006. Variation of different tree-ring parameters in samples from each terminal shoot of a Norway spruce tree. *Dendrochronologia* 23(3):1 11-20.

- Helama, S., M. Lindholm, M. Timonen & M. Eronen. 2004. Detection of climate signals in dendrochronological data analysis: a comparison of tree-ring standardization methods. *Theoretical and Applied Climatology* 79: 239-254.
- Helle, G. 1996. Hochauflösende intra-annuelle Kohlenstoff-Isotopenuntersuchungen an Baumjahresringen. Dissertation, Westfälische Wilhelms-University Münster.
- Helle, G., G.H. Schleser. 2004. Beyond CO₂-fixation by Rubisco – An interpretation of ¹³C/¹²C variations in tree rings from novel intra-seasonal studies on broadleaf trees. *Plant, Cell and Environment* 27: 367-380.
- Hemming, D.L., V.R. Switsur, J.S. Waterhouse, T.H.E. Heaton & A.H.C. Carter. 1998. Climate variation and the stable carbon isotope composition of tree ring cellulose: an intercomparison of *Quercus robur*, *Fagus sylvatica*, and *Pinus silvestris*. *Tellus, Series B: Chemical and Physical Meteorology* 50B: 25-33.
- Holmes, R.L. 1983. Computer assisted quality control in tree-ring dating and measurements. *Tree Ring Bull* 43: 69-75.
- Keeling, C.D., A.F. Bollenbacher & T.P. Whorf. 2005. Monthly atmospheric ¹³C/¹²C isotopic ratios for 10 SIO stations. In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee.
- Kleinbaum, D.G., L.L. Kupper & K.E. Muller. 1988. *Applied Regression Analysis and Other Multivariable Methods*. PWS-KENT Publishing Company, Boston. 2nd edition.
- Krause, C. 1992. Ganzbaumanalyse von Eiche, Buche, Kiefer und Fichte mit dendroökologischen Methoden. Dissertation, University of Hamburg.
- Latscha, H.P., A.A. Klein & R. Mosebach. 1988. *Chemie für Pharmazeuten und Biologen I – Allgemeine und Anorganische Chemie*. Springer-Verlag Berlin, Heidelberg.
- Leavitt, S.W. & A. Long. 1986. Stable-carbon isotope variability in tree foliage and wood. *Ecology* 67(4): 1002-1010.
- Liebert, S. 1996. Eichenchronologien im Raum Wien, 1462 – 1995. Masterthesen, Universität für Bodenkultur Wien.
- Loader, N.J., I. Robertson, A.C. Barker, V.R. Switsur & J.S. Waterhouse. 1997. An improved technique for the batch processing of small wholewood samples to α-cellulose. *Chemical Geology* 136: 313-317.
- Loader, N.J., I. Robertson & D. McCarroll. 2003. Comparison of stable carbon isotope ratios in the whole wood, cellulose and lignin of oak tree-rings. *Palaeogeography, Palaeoclimatology, Palaeoecology* 196(3-4): 395-407.

- Mayr, C., B. Frenzel, M. Friedrich, M. Spurk, W. Stichler & P. Trimborn. 2003. Stable carbon- and hydrogen-isotope ratios of subfossil oaks in southern Germany: methodology and application to a composite record for the Holocene. *The Holocene* 13(3): 393-402.
- Mook, W.G., M. Koopmans, A.F. Carter & C.D. Keeling. Seasonal, latitudinal, and secular variations in the abundance and isotopic ratios of atmospheric carbon dioxide. 1. Results from land stations. *Journal of Geophysical Research* 88: 10915-10933.
- Nola, P. 1996. Climatic signals in earlywood and latewood of deciduous oaks from northern Italy. In: Dean, J.S., D.M. Meko & T.W. Swetnam (ed.), *Proceedings of the international Conference Tree Ring, Environment and Humanity*, University of Arizona: 249-258.
- Ogle, N., C. Turney, R. Kalin, L. O'Donnell & C. Butler C. 2005. Palaeovolcanic forcing of short-term dendroisotopic depletion: The effect of decreased solar intensity on Irish oak. *Geophysical Research Letters* 32(4): doi:10.1029/2004GL021623.
- Pazdur, A., S. Korput, M. Fogtman, M. Szczepanek, S. Halas, M. Krapiec & E. Szychowska-Krapiec. 2005. Carbon-13 in α -cellulose of oak latewood (Jedrzejow, Southern Poland) during the Maunder Minimum. *Geological Quarterly* 49(2): 165-172.
- Pilcher, J.R. & B. Gray. 1982. The relationships between oak tree growth and climate in Britain. *Journal of Ecology* 70: 297-304.
- Protoschill, J. 1998. Umweltrelevanz von $\delta^{13}\text{C}$ -Variationen in Jahrringen gesunder und kranker Eichen. Research Centre Jülich (FZJ), ICG4-IB-5004/98.
- Rinn, F. 1996. TSAP. Time Series Analysis and Presentation. Version 3.0, Reference Manual.
- Rinn, F. 2003. TSAP-Win Professional Time Series Analysis and Presentation for Dendrochronology and Related Applications. Version 0.3, Quick Reference.
- Roeske, C.A. & M.H. O'Leary. 1984. Carbon isotope effects on the enzyme-catalysed carboxylation of ribulose bisphosphate. *Biochemistry* 23: 6275-6284.
- Roloff, A. 2001. Baumkronen, Ulmer Eugen Verlag, Stuttgart, Germany
- Rozanski, K., L. Araguás-Araguás & R. Gonfiantini. 1992 Relation Between Long-Term Trends of Oxygen-18 Isotope Composition of Precipitation and Climate. *Science* 258: 981-984.
- Sass-Klaassen, U., I. Poole, T. Wils, G. Helle, G.H. Schleser & P.F. van Bergen. 2005. Carbon and oxygen isotope dendrochronology in sub-fossil bog oak tree rings - a preliminary study. *IAWA Journal* 26(1): 121-136.
- Saurer, M., S. Borella & M. Leuenberger. 1995a. $\delta^{18}\text{O}$ of tree rings of beech (*Fagus silvatica*) as a record of $\delta^{18}\text{O}$ of the growing season precipitation. *Tellus* 49B: 80-92.
- Saurer, M., U. Siegenthaler & F. Schweingruber. 1995b. The climate-carbon isotope relationship in tree rings and the significance of site conditions. *Tellus* 47B: 320-330.

- Saurer, M., S. Borella, F.H. Schweingruber & R. Siegwolf. 1997. Stable carbon isotopes in tree rings of beech: climatic versus site-related influences. *Trees* 11: 291-297.
- Scheidegger, Y., M. Saurer, M. Bahn & R. Siegwolf. 2000. Linking stable oxygen and carbon isotopes with stomatal conductance and photosynthetic capacity: a conceptual model. *Oecologia* 125: 350-357.
- Schleser G.H. 1992. $\delta^{13}\text{C}$ pattern in a forest tree as an indicator of carbon transfer in trees. *Ecology* 73(5): 1922-1925.
- Schleser, G.H. 1999. $^{13}\text{C}/^{12}\text{C}$ in growth rings and leaves: carbon distribution in trees. In: Jones, T.P. & N.P. Rowe (ed.), *Fossil Plants and Spores: modern techniques*, Geological Society, London: 306-309.
- Schweingruber, F.H. 1983. *Der Jahrring: Standort, Methodik, Zeit und Klima in der Dendrochronologie*. Verlag Paul Haupt, Bern, Stutgard.
- Schweingruber, F.H. 1993. *Jahrringe und Umwelt – Dendroökologie*. Birmensdorf, WSL.
- Schweingruber, F.H. 2001. *Dendroökologische Holzanatomie: Anatomische Grundlagen der Dendrochronologie*. Verlag Paul Haupt, Berne.
- Siegenthaler, U. & H. Oeschger. 1980. Correlation of ^{18}O in precipitation with temperature and altitude. *Nature* 285: 314-317.
- de Silva, M.P. 1978. ^{13}C -Variationen in Baumjahresringen als Folge des anthropogenen CO_2 -Anstiegs der Atmosphäre: Untersuchung des Einflusses von Klimaparametern. Research Centre Jülich (FZJ).
- Stokes, M.A. & T.L. Smiley. 1996. *An Introduction to Tree-Ring Dating*. The University of Arizona Press, Tucson.
- Strackee, J. & E. Jansma. 1992. The statistical properties of mean sensitivity - a reappraisal. *Dendrochronologia* 10: 121-135.
- Stuiver, M. 1978. Atmospheric carbon dioxide and carbon reservoir changes. *Science* 199: 253-258.
- Swetnam, T.W., M.A. Thompson & E.K. Kenedy-Sutherland. 1985. Using dendrochronology to measure radial growth of defoliated trees. *USDA Forest Service Agricultural Handbook 639*, Washington D.C.
- Tans, P. & W.G. Mook. 1980. Past atmospheric CO_2 levels and the $^{13}\text{C}/^{12}\text{C}$ ratios in tree rings. *Tellus* 68: 268-283.
- Tardif, J. 1996. Earlywood, latewood and total ring width of a ring-porous species (*Fraxinus nigra* Marsh.) in relation to climatic and hydrologic factors In: Dean, J.S., D.M. Meko & T.W. Swetnam (ed.), *Proceedings of the international Conference Tree Ring, Environment and Humanity*, University of Arizona: 315-324.

- Treydte, K.S. 2002. Dendro-Isotope und Jahrringbreiten als Klimaproxis der letzten 1200 Jahre im Karakorumgebirge/Pakistan. Dissertation, University of Bonn.
- Treydte, K., J. Esper & H. Gärtner. 2004. Stabile Isotope in der Dendroklimatologie. Schweizerische Zeitschrift für Forstwesen 155(6): 222-232.
- Treydte, K., G.H. Schleser, J. Esper, L. Andreu, T. Bednarz, J. Berninger, T. Böttger, C.D. D'Allessandro, N. Ethien, M. Filot, D. Frank, M. Grabner, E. Gutierrez, M. Haupt, G. Helle, H. Jungner, M. Kalela-Brundin, M. Leuenberger, N. Loader, V. Masson-Delmotte, A. Pazdur, O. Planells, R. Pukiene, C. Reynolds, K. Rinne, M. Saurer, E. Soninen, M. Stievenard, R. Switsur, M. Szczepanek, L. Todaro, J. Waterhouse, M. Weigl & R. Wimmer 2005. The European Isotope Network ISONET: First Results. TRACE, Tree Rings in Archeology, Climatology and Ecology, 21.-23. April 2005, Fribourg
- Weigl, M., M. Grabner & R. Wimmer. 2004. Comparison of earlywood-width, latewood-width and total ring-width measurements on oak (*Quercus petraea* Liebl.). In: Eckstein, D. & S. Wrobl (ed.), Eurodendro 2004, International Conference of Dendrochronology, University of Hamburg: 52-53.
- Weigl, M., M. Grabner, R. Wimmer, G. Helle & G. Schleser. 2005. Studying radial and axial variation of stable isotopes within a single oak tree. In: Scarlatto, M., A. Di Filippo, G. Piovesan & M. Romagnoli (ed.), Eurodendro 2005, International Conference of Dendrochronology, University of Tuscia: 39-40.
- Weigl, M., M. Grabner, G. Helle, G. Schleser & R. Wimmer. 2006. Variability of latewood-widths and -stable isotope ratios in a sessile oak tree (*Quercus petraea* (Matt.) Liebl.). Dendrochronologia, in press
- White, J.W.C., E.R. Cook, J.R. Lawrence and W.S. Broecker. 1985. The D/H ratios of sap in trees: implications for water sources and tree ring D/H ratios. *Geochimica et Cosmochimica Acta* 49: 237-246.
- Wrobl, S. & D. Eckstein. 2005. An everlasting question with archeological wooden samples: which ones come from one and the same stem? In: Scarlatto, M., A. Di Filippo, G. Piovesan & M. Romagnoli (ed.), Eurodendro 2005, International Conference of Dendrochronology, University of Tuscia: 40.
- Yakir, D. 1992. Variations in the natural abundance of oxygen-18 and deuterium in plant carbohydrates. *Plant, Cell and Environment* 15: 1005-1020.
- Zhang, S.Y., G. Nepveu & R. Eyono Owoundi. 1994. Intratree and intertree variation in selected wood quality characteristics of European oak (*Quercus petraea* and *Quercus robur*). *Canadian Journal of Forest Research* 24: 1818-1823.

Zhang, S.Y. 1997. Variations and correlations of various ring with and ring density features in European oak: implications in dendroclimatology. *Wood Science and Technology* 31: 63-72.