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An investigation of the common signal in tree ring stable isotope chronologies at temperate sites

M. Saurer,[1] P. Cherubini,[2] C. E. Reynolds-Henne[1,3] K. S. Treydte,[2] W. T. Anderson,[4]
and R. T. W. Siegwolf[1]

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[1] It is currently not well known how coherent carbon and oxygen isotope chronologies from different species and sites are under temperate climate conditions. Here we investigated nine chronologies from Switzerland covering the last two centuries, including three deciduous species (*Fagus sylvatica*, *Fraxinus excelsior*, and *Quercus petraea*) and three conifer species (*Abies alba*, *Picea abies*, and *Pinus sylvestris*) from sites neither strongly limited by temperature nor precipitation. All of the chronologies except *Fraxinus* were significantly correlated to at least one other chronology. Correlations between different species of the same site were of similar strength to correlations between the sites. We observed a strong common high-frequency (interannual) signal for the δ^{13}C chronologies, whereas the low-frequency (decadal-scale) signal was more similar among the δ^{18}O chronologies. For both carbon and oxygen isotopes, we found significant positive relationships with annual and growing season temperatures and negative relationships with precipitation, again of similar magnitude for all species except for *Fraxinus*, which contained only minor climatic information. Averaging of all chronologies resulted in an increase in the climatic signal of the mean chronology. The combined δ^{18}O record reflected decadal-scale temperature variations remarkably well (r = 0.72). However, the relationship between climate and carbon isotopes declined over the last 3 decades of the 20th century, probably related to the steep increase in atmospheric CO_2 concentrations, resulting in strongly diverging δ^{13}C trends of the different chronologies. Our study indicates that combining chronologies from different species enhances the potential of isotope studies for extending climate reconstructions into areas of temperate climate.

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1. Introduction

[2] Tree ring width and density variations are widely used to reconstruct past climatic conditions, such as air temperature and precipitation. This method is most successful at sites where only one climatic factor clearly limits tree growth, for example at latitudinal or altitudinal tree limits or close to deserts [*Briffa et al.*, 2002; *Cook et al.*, 2004; *Esper et al.*, 2002; *Schweingruber*, 1988]. In temperate forests, however, tree growth is influenced by many different environmental factors (climate included) so that tree ring width and density are less useful in unambiguous climatic reconstructions. It has been suggested that tree ring stable isotopic variations might be not as strongly dependent on local site conditions as growth and therefore isotope studies might have the potential to extend climate reconstructions from extreme to more temperate regions [*McCarroll and Loader*, 2004; *Saurer et al.*, 1995]. Yet, the tree ring isotope archive is not a purely physical archive, but also reflects biological processes. Several studies have observed that the isotope variations in leaves and wood of trees depend on the ecological site conditions, both for carbon and oxygen isotope ratios [*Barbour et al.*, 2001; *Loader and Rundgren*, 2006; *Wang and Yakir*, 1995]. At dry sites, for instance, the carbon isotope ratio may provide more information on precipitation variations than at comparably wet sites, similar to what is known for tree ring width variations [*Leavitt and Long*, 1989]. Furthermore, different species growing at the same site may not exactly be influenced in the same way by climate. Some tree species may be more sensitive to a certain climatic factor than others, physiological properties may be different between tree species, and different rooting depths may result in different responses to long-term climatic changes, in particular to drought stress [*Marshall and Monserud*, 2006; *Tsuji et al.*, 2006].

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[1] Paul Scherrer Institut, Villigen PSI, Switzerland.

[2] WSL Swiss Federal Research Institute, Birmensdorf, Switzerland.

[3] Now at Institute of Plant Sciences, University of Bern, Bern, Switzerland.

[4] Earth Sciences Department and Southeast Environmental Research Center, Florida International University, Miami, Florida, USA.

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[3] Therefore, it is important to assess the common signal of different isotope tree ring chronologies in a certain region. Assuming that a high degree of coherence would be found under temperate climate conditions, this would indicate (1) the relative independence of site and species, (2) the existence of a common climate signal, (3) the potential for averaging several chronologies to get a more reliable regional climate reconstruction, and (4) the possibility of building networks. Showing a common signal would open an avenue for a similar approach as already applied for ring width and density. At sites limited by temperature or precipitation, ring width networks including many sites and species have been built, for instance, in the arid western U.S. for reconstructing drought [*Cook et al.*, 2004; *Meko et al.*, 1993] and in the Alps for reconstructing summer temperature [*Büntgen et al.*, 2006; *Büntgen et al.*, 2005; *Frank and Esper*, 2005]. One of the first densitometric networks was built for conifer sites across the northern hemisphere to reconstruct past summer temperatures at high latitudes [*Briffa et al.*, 2002; *Schweingruber et al.*, 1993]. In this investigation, species differences in the response to climate were observed (*Larix* showed a stronger temperature signal than *Pinus* and *Picea*), but as long as restricted to relatively uniform and strongly limited sites, regional averaging over different species still increased the signal-to-noise ratio [*Briffa et al.*, 2002]. Combining ring width and/or density records of many trees, species and sites therefore ultimately results in more reliable climate reconstructions [*Baillie*, 1995; *Cook et al.*, 2004; *Esper et al.*, 2005].

[4] While a relatively large number of stable isotope dendroclimatology studies exist [*McCarroll and Loader*, 2004], most isotopic reconstructions comprise trees from a single site and little is known about the common signal of different chronologies, in particular for temperate sites. Regarding carbon isotopes, some studies have investigated the similarity of the isotope signal from different species growing at one site [*Hemming et al.*, 1998], compared chronologies from different sites [*Leavitt and Long*, 1988], along altitudinal [*Treydte et al.*, 2001] or along latitudinal transects [*Arneth et al.*, 2002]. In these studies, generally a good agreement among different chronologies was reported, while other results point to a significant dependence on landscape and environmental variables, such as the availability of water, nutrient and light [*Warren et al.*, 2001]. Regarding oxygen isotopes, in particular, there is a great lack of comparisons of different sites and species. To our knowledge, no study has yet compared δ^{18}O tree ring series from several deciduous and conifer species, apart from a study comparing average site values across the globe [*Barbour et al.*, 2001]. Network approaches recently evolving provide the means for assessing isotope variability on a large scale, e.g., on a European scale [*Treydte et al.*, 2007], but are rather designed to investigate real spatial variability in the climate signal, not common isotope signals on a regional scale.

[5] In this study, we analyzed nine isotope chronologies from Switzerland (three new and six already published series), comprising the deciduous species *Fagus sylvatica*, *Fraxinus excelsior*, *Quercus petraea* and the conifer species *Abies alba*, *Picea abies*, *Pinus sylvestris* covering the last 100–200 years. All investigated sites are lowland sites, with tree growth neither strongly limited by temperature nor water availability, situated within an area of approximately 100 × 150 km. The data set offers a unique possibility for assessing the common signal among different species and sites for carbon as well as oxygen isotopes and for determining the climatic significance of a combined (all species/sites) chronology.

2. Materials and Methods

2.1. Site Description

[6] Three of the investigated sites are situated in the Swiss Central Plateau (“Twann,” “Koppigen” and “Eigentobel”), one is located on the southern borders of the Jura mountain chain (“Bettlachstock”) and two are located South of the Alps (“Ticino I” and “Ticino II”), as shown in Figure 1. The climate for the sites north of the Alps is temperate-moist, the annual precipitation sum is about 1100 mm and the annual average temperature 9°C. At the site Twann (7°10′E 47°5′N), beech trees (*Fagus sylvatica*, abbreviated *FS*-Twa) were investigated. The site is located on a southeastern slope on shallow soil and is relatively dry [*Saurer et al.*, 1997]. Table 1 shows an overview of site parameters. The site Bettlachstock (7°25′E, 47°13′N) is a Swiss Long-Term Forest Ecosystem Research plot (WSL Birmensdorf), also located on a southern slope. The species investigated include *Fraxinus excelsior*, *Abies alba*, *Picea abies* and *Fagus sylvatica*, labeled as *FE*-Bet, *AA*-Bet, *PA*-Bet, and *FS*-Bet. Data from *AA*-Bet have been discussed in [*Saurer et al.*, 2000], whereas *FE*-Bet, *PA*-Bet and *FS*-Bet have not previously been published. The site Koppigen is located on flat terrain (7°35′E, 47°8′N), with a densely packed silty soil (pseudo-gley), and *Picea abies* (*PA*-Kop) trees were sampled [*Saurer et al.*, 2004a]. The site Eigentobel (8°15′E, 47°10′N) is located on a 10° to 20° south facing slope, where *Picea abies* (*PA*-Eig) trees were investigated [*Anderson et al.*, 1998]. The sites south of the Alps, Ticino I and Ticino II, were studied in detail in the EU-Project ISONET [*Reynolds-Henne et al.*, 2007]. The climate in southern Switzerland has a moderate Mediterranean influence with higher average annual temperature (12°C) than north of the Alps. Yearly precipitation sums are in the same range (1150 mm), but with differing seasonal distribution (summer maximum in the north versus winter/spring maximum in the south). The studied site is known as one of the oldest oak stands in the Swiss Alps with tree ages up to 450 years (G. Carrero, personal communication, 2006). Ticino I (8°36′E, 46°21′N, 900 m above sea level) is on a steep southern slope (40°), with shallow Rendzina-type soil (40–50 cm), where oak trees were sampled (*Quercus petraea*, *QP*-Tic). At Ticino II (8°46′E, 46°30′N) *Pinus sylvestris* (*PS*-Tic) trees were investigated (Podzolic ranker soil, shallow 30–40 cm). Overall, the sites are relatively well-drained, the altitudinal range covers 480 to 1400 m asl, while maximum distance between the sites is 160 km (from Twann to Ticino II).

2.2. Sample Preparation and Analysis

[7] Four trees were sampled at all sites (2 cores per tree), tree ring cores were dated and individual rings separated with a razor blade under a microscope. As the individual sites were not all investigated within the same project, several differences in the preparation protocol exist. Cellu-

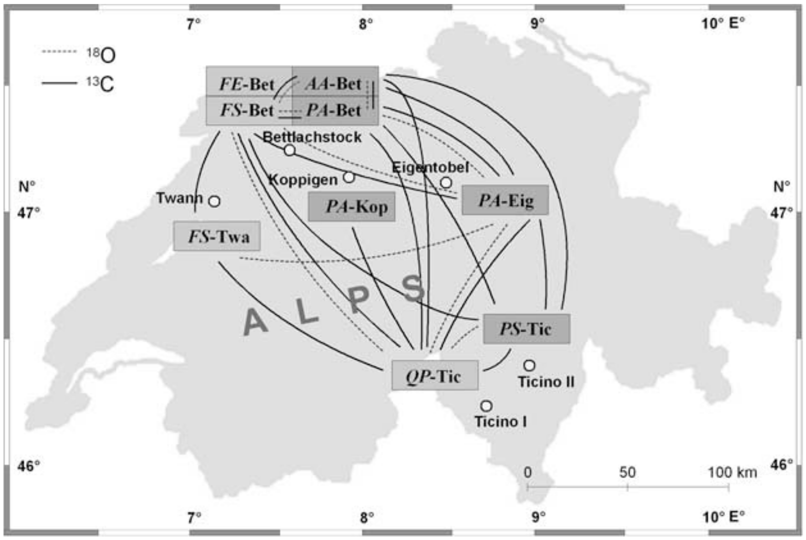

Figure 1. Map of Switzerland with site location and species investigated (light color for deciduous and dark color for coniferous species). The lines indicate all significant correlations between the different isotope chronologies in the common period 1913–1995 (dotted lines for δ^{18}O; solid lines for δ^{13}C; $p < 0.05$).

lose was extracted from the samples from *FS*-Twa, *PA*-Eig, *QP*-Tic and *PS*-Tic, but whole wood was analyzed for *PA*-Kop and all Bettlachstock series (Table 1). Cellulose and whole wood contain similar information in the isotope ratios, but an offset between the two materials has to be considered, which is 1–2‰ for δ^{13}C and 3–4‰ for δ^{18}O [*Barbour et al.*, 2001; *Borella et al.*, 1999]. While cellulose is often considered to be slightly more reliable as a climate proxy, in some cases whole wood proved to be more closely related to instrumental data [*Loader et al.*, 2003]. Tree rings including early and latewood were analyzed for *QP*-Tic and *PS*-Tic and *PA*-Eig, latewood only was analyzed for the Bettlachstock series, whereas samples from *FS*-Twa and *PA*-Kop comprised 3-year blocks (therefore also containing a combined early and latewood signal). The latter two sites were obviously not considered in all analyses that are based on annual resolution. Individual trees were analyzed for *FS*-Twa and *PA*-Kop, whereas a pooling approach was used at the other sites where the same year from different tree cores was combined before processing further (sampling several individuals from one site to provide a site chronology [*Borella et al.*, 1998; *Leavitt and Long*, 1984; *Treydte et al.*, 2001]). The first approximately 30 years of tree age were not used for the isotope analysis to reduce the influence of the juvenile effect [*Leavitt and Long*, 1989]. The analysis in this paper is focused on the period 1800–2000. Accordingly, the full length of the measured record was considered in this analysis for the sites north of the Alps, which do not extend further back than 1800, whereas the oldest part of the record for the sites south of the Alps was not considered here (Table 1) [*Reynolds-Henne et al.*, 2007]. Oxygen isotope analyses were carried out by thermal decomposition on glassy carbon and carbon isotope analysis by combustion, using an elemental analyzer which was connected to an isotope ratio mass spectrometer (delta-S, Finnigan), except for the samples from Twann, which were measured with an off-line pyrolysis method [*Saurer et al.*, 1998]. Carbon isotope values are referred to VPDB (δ^{13}C), while oxygen isotope values are referred to VSMOW (δ^{18}O). The precision of the analysis was better than 0.2‰ for δ^{13}C and better than 0.3‰ for δ^{18}O.

2.3. Data Analysis

[8] The δ^{13}C data were all corrected for the decline of δ^{13}C in atmospheric CO_2 due to fossil fuel emissions according to data from [*Francey et al.*, 1999]. This correction is necessary, because the data would otherwise show a trend which is not related to climate but to the change in the source value of the CO_2 used by the plants [*McCarroll and Loader*, 2004]. All evaluations were carried out on δ^{13}C and

Table 1. Site Information, Time Periods Analyzed, and Sample Preparation

Site Code	Altitude (m asl)	Period	Wood/Cellulose	Time-Resolution	Latewood/Whole Ring
FE-Bet	1150	1841–1995	wood	annual	latewood
FS-Bet	1150	1864–1995	wood	annual	latewood
AA-Bet	1150	1840–1997	wood	annual	latewood
PA-Bet	1150	1801–1995	wood	annual	latewood
FS-Twa	600	1934–1986	cellulose	3-year blocks	whole ring
PA-Kop	480	1916–2000	wood	3-year blocks	whole ring
PA-Eig	600	1913–1995	cellulose	annual	whole ring
QP-Tic	900	1637–2002	cellulose	annual	whole ring
PS-Tic	1400	1675–2003	cellulose	annual	whole ring

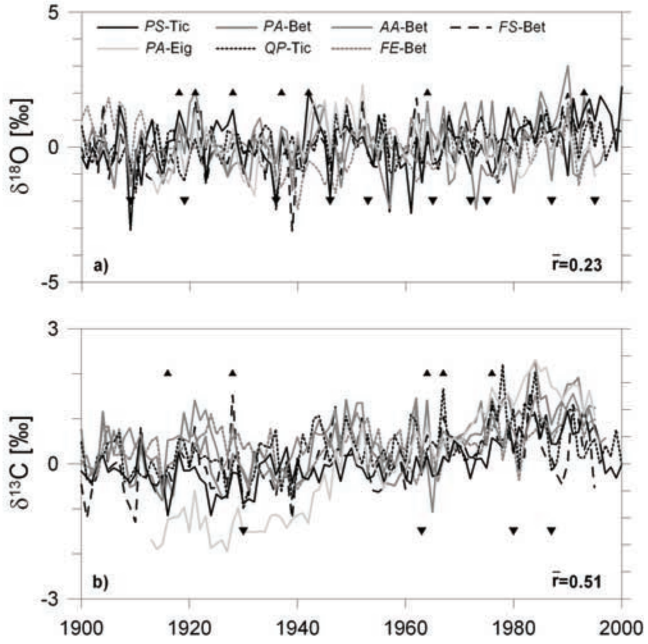

Figure 2. Anomalies of the isotope chronologies (residuals from the mean) with annual resolution during the 20th century. (a) Oxygen isotopes. (b) Carbon isotopes. The triangles indicate years where six or seven chronologies show a change of more than 0.3‰ in the same direction (positive change: triangle pointing upward, and vice versa). The mean interseries correlation ($\bar{r}$) is also given.

δ^{18}O anomalies, defined as differences between individual isotope values and the average of each series. By this calculation, a simple subtraction, offsets in the absolute values for cellulose and whole wood and differences between species are corrected for, while all low- to high-frequency variations are preserved.

[9] Correlation analyses with climatic data were done for two time windows: (1) For the common period 1913–1995 using all sites with annual resolution and comparison with monthly climate data (seven sites) and (2) for the combined 200-year isotope record with 9-year running averages for both isotopes and climate (nine sites). Nine-year running averages were calculated to assess decadal-scale variability because 2 of the chronologies were based on the analysis of 3-year blocks. We used climatic data from [*Casty et al.*, 2005; *Mitchell and Jones*, 2005], a record that provides monthly temperature and precipitation data at 0.5° grid resolution for the whole investigated period. Climate data of the grid cells centered around 7.75°E/47.25°N and 8.75°E/47.25°N were used for the sites north of the Alps, and centered around 8.75°E/46.25°N for the sites south of the Alps. We preferred to use gridded data over local station data because of the overall goal of investigating regional climate signals. Furthermore, the gridded data set was also crosschecked against the local temperature and precipitation of three stations (Bern, Zurich, Lugano) for the period 1864–2000. For instance, the data for the grid cell containing Zurich were correlated with Zurich station data, yielding r^2 = 0.84 for monthly July temperature, and r^2 = 0.57 for July precipitation. For a comparison with the combined isotope chronology, climate data of the above three grid cells have been averaged. This is justified because at least the temperature variations in the high to low frequencies have been shown to be rather uniform over the Greater Alpine Region [*Böhm et al.*, 2001]. Indeed, regarding 9-year running averages, the data from grid cells used in this analysis north and south of the Alps are highly correlated for summer temperature (r = 0.99) as well as summer precipitation (r = 0.80), annual temperature (r = 0.98), but less for annual precipitation (0.30).

[10] The significance of linear correlation coefficients for the climate-isotope relationship was tested using a bootstrap procedure [*Biondi and Waikul*, 2004]. The level of significance was $p < 0.05$. For the correlation analysis between different isotope chronologies, a reduced degree of freedom due to lag-1 autocorrelation r_1 was applied as $N' = N(\frac{1-r_1}{1+r_1})$ (effective sampling size [*Dawdy and Matalas*, 1964]) and a t-test applied. Some analysis involved combining records of different length which required a special offset correction: Instead of considering the average of the whole record (as done for the anomalies described above), only the average of the first 30 years was adjusted to the average of the older series. This procedure removed artificial steps potentially caused by a new series entering the combined chronology. This latter correction was only applied for the analysis of the full record (1803–1998), but not for the analysis of the common period 1913–1995 at annual resolution. For correlations of 9-year running averages, a simple formula for the reduced degree of freedom of (N-1)/9 was used.

3. Results

3.1. Overview on 20th Century Isotope Variations

[11] The oxygen isotope anomalies for the different species and sites show a similar course over the last 100 years (Figure 2a), considering that the chronologies were not detrended in any way, but simply corrected by an offset. First, the curves are similar in the absence of a trend over the course of the century and second they show many similarities regarding the short-term fluctuations. We determined the years where at least six (out of seven) chronologies show the same direction of change of greater than 0.3‰. These years include 1918, 1921, 1928, 1937, 1942, 1964, 1993 (positive change), and 1909, 1919, 1936, 1946, 1953, 1965, 1972, 1975, 1987, 1995 (negative change), see also arrows in Figure 2. The carbon isotope chronologies show more lower-frequency variability compared to the oxygen isotope series (Figure 2b). These trends again are similar for all species and sites, with the exception of *PA*-Eig which shows strongly increasing δ^{13}C values with time. Years with the same direction of change of at least 0.3‰ on six or seven sites include 1916, 1928, 1964, 1967, 1976 (positive change) and 1930, 1963, 1980, 1987 (negative change). Accordingly, some of these "event years" were observed for both carbon and oxygen, namely 1928, 1964 (positive change for both isotopes), and 1987 (negative change for both isotopes). It never occurred that a positive event year of one isotope would coincide with a negative event year of the other isotope.

3.2. Correlation Between the Chronologies

[12] There are numerous significant correlations between the different isotope chronologies, indicated in Figure 1

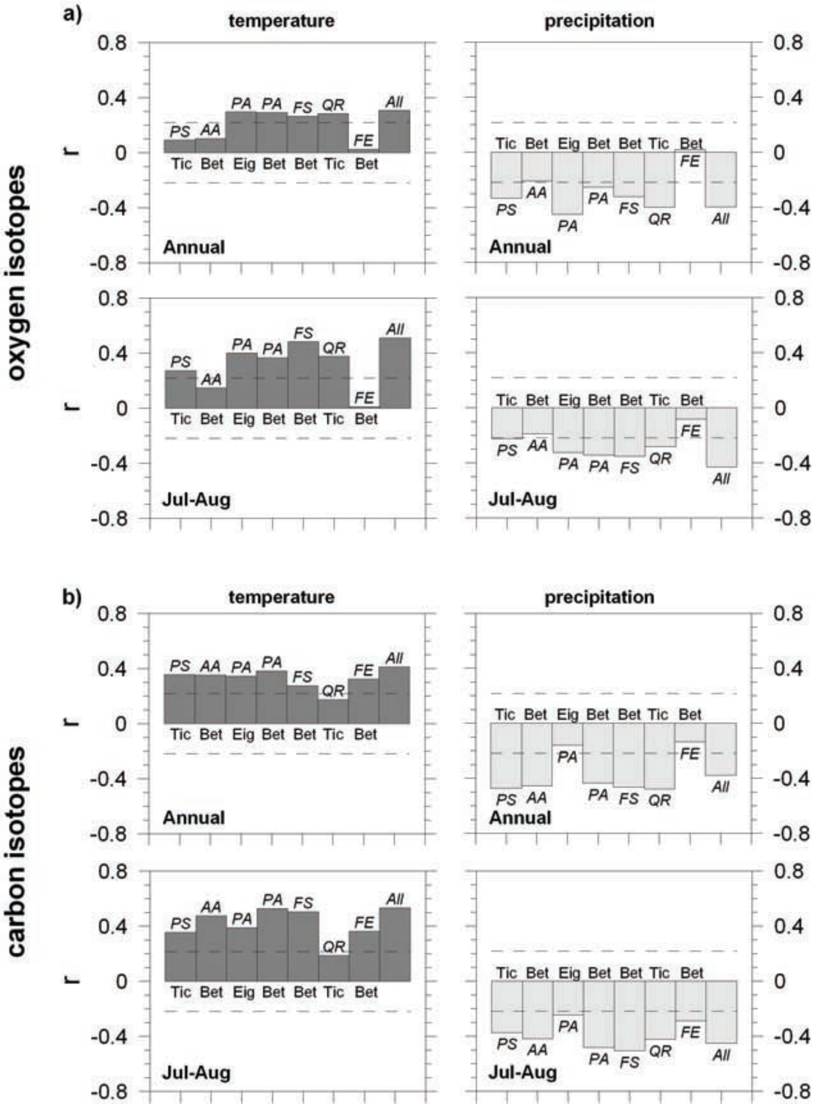

Figure 3. Correlation coefficients (r) describing the relationship of (a) δ^{18}O and (b) δ^{13}C with climate data for the period 1913–1995, shown separately for temperature and precipitation for annual and July–August averages. Each bar reflects the correlation for one chronology, while the rightmost bar reflects the correlation to the combined isotope chronology. Dotted lines are $p < 0.05$ significance levels.

with connecting lines, as evaluated for the common period 1913–1995. Overall, the δ^{13}C series show more similarities to each other (18 significant relationships) compared to the δ^{18}O series (9 significant relationships), while the total number of pairwise relationships is 36. This difference is reflected in a higher interseries correlation (average correlation coefficient) for δ^{13}C ($\bar{r}$ = 0.51) compared to only $\bar{r}$ = 0.23 for δ^{18}O. This is partly caused by the high autocorrelation in the δ^{13}C series due to similarly increasing long-term trends, which was, however, taken into account in the calculations of the significance by a reduced effective sampling size (degree of freedom). The within-site relationships at Bettlachstock ($\bar{r}$ = 0.48 for δ^{13}C; $\bar{r}$ = 0.25 for δ^{18}O) are not higher than the between-site relationships, to some degree caused by the very different behavior of one chronology (*Fraxinus*, *FE*-Bet), which is not significantly ($p > 0.05$) related to any other series. From Figure 1, it is apparent that there are no clear patterns regarding deciduous or conifer species or the distance between the sites: The sites south of the Alps are correlated with many sites north of the Alps. Many deciduous tree chronologies are related to conifer chronologies. In addition to *FE*-Bet, the two series *FS*-Twa and *PA*-Kop appear to be not as well connected to the rest of the network, but this could be caused by the lower resolution and lower sample size for these two sites (3-year blocks analyzed). The overall highest correlation coefficients were observed for the relationship between *PA*-Eig and *PA*-Bet (r = 0.83) for δ^{13}C, and between *PA*-Bet and *FS*-Bet (r = 0.68) for δ^{18}O.

3.3. Correlation Between Isotopes and Climate: Annual Resolution

[13] The 7 chronologies at annual resolution were correlated to monthly values of temperature and precipitation for the common period 1913–1995. While the analysis was conducted for individual months of the current and previous

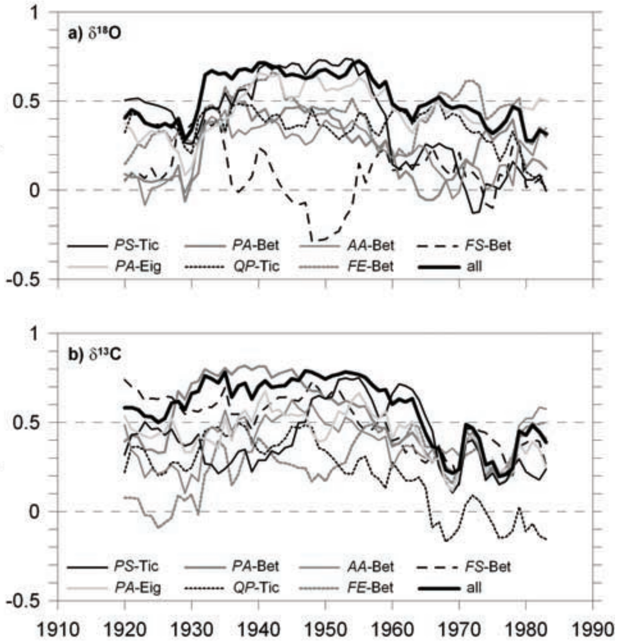

Figure 4. Moving correlation (*r*) with 20-year window for the correlation between the isotope chronologies and July–August temperature (common period 1913–1995). (a) The relationship for δ^{18}O. (b) The relationship for δ^{13}C.

year, the most significant relationships resulted for annual and summer (July–August) averages. Therefore only these results are presented. For δ^{18}O (Figure 3a), positive correlation coefficients are observed with temperature, and negative coefficients with precipitation. All chronologies except *FE*-Bet are significantly related to temperature and precipitation for at least one of the two periods investigated (annual climate values; July–August), with slightly higher correlations for temperature (maximum *r*-values ~0.5) than for precipitation. The average δ^{18}O curve of all species and sites is often more strongly correlated to climate (which is in this case an average of grid cells north and south of the Alps) than any individual chronology (see Figure 3, right-most bars). This holds despite the inclusion of the *FE*-Bet series into the average which is not correlated to climate at all. The improvement observed for the average curve can be shown by the following calculation, concerning the correlation of δ^{18}O to July–August temperature: The average of the correlation coefficients $\bar{r}$ for individual chronologies is only 0.29, while the correlation coefficient for the average chronology correlated to July–August temperature is 0.51. Regarding the correlation to July–August precipitation, the respective numbers are $\bar{r} = -0.26$ (average for individual series) and $r = -0.43$ (value for the average chronology).

[14] For δ^{13}C (Figure 3b), we find similar results. Correlations to temperature are always positive, while correlations to precipitation are negative. Overall, the different species and sites show a similar response. The strength of the correlations is of the same order of magnitude as for δ^{18}O. *FE*-Bet is not so evidently an outlier as in the case of oxygen isotopes. *QP*-Tic is relatively weakly connected to temperature, and *PA*-Eig to precipitation. As for the oxygen isotopes, the average chronology is well correlated to climate (correlation to July–August temperature $r = 0.54$), but the improvement over the average of individual chronologies is not so strong ($\bar{r} = 0.40$). The respective numbers for July–August precipitation are $\bar{r} = -0.39$ (average for individual series) and $r = -0.45$ (value for the average chronology).

[15] In addition to these simple regressions, we further applied a multiple linear regression model to predict the climate parameter on the basis of the combined information of the two isotopes. For temperature (T) this model can be expressed as $T = a_1{*}\delta^{18}O + a_2{*}\delta^{13}C + c_1$. A similar equation can also be written for precipitation. For July–August temperature, we found that the correlation coefficients for the multiple regression model are generally somewhat higher than the simple linear regression coefficients shown in Figure 3. In particular, there was less variability between the species, with coefficients ranging between $r = 0.42$ (*FE*-Bet) and $r = 0.58$ (*FS*-Bet). For the correlation with the species average $r = 0.60$ resulted, where the coefficients a_1 and a_2 contributed with a similar weight. Regarding the multiple linear regression with July–August precipitation, *r* ranged from 0.30 (*FE*-Bet) to 0.54 (*FS*-Bet).

3.4. Stability of the Climate-Isotope Relationship

[16] The stability of the (simple) linear correlations between climate and isotopes over the 20th century was studied by a moving window technique (running correlations for a 20-year period). This analysis was carried out for correlations with July–August temperature because these relationships were strongest in the above analysis. We observed that the correlations of the isotope ratios with July–August temperature show a marked decrease after about 1960, in particular for δ^{13}C (Figure 4b). While the correlations for all δ^{13}C chronologies (except *FE*-Bet) were consistently positive and reaching $r = 0.8$ before 1960, they clearly fall below 0.5 afterward, *QP*-Tic even to about zero. A similar, but less pronounced pattern is observed for the δ^{18}O chronologies, with a decrease in the correlation strength after about 1955 (Figure 4a).

3.5. Decadal-Scale Variability

[17] Nine-year running averages were considered for studying the decadal-scale variability in the isotope chronologies. As apparent from Figure 5a, the different δ^{18}O chronologies show many common variations. Only the record of *FE*-Bet is quite different, as already noted above. The most remarkable pattern consistent throughout almost all chronologies is the period of high values in the late 1940s/beginning of 1950s. The conifer species (shown in the upper part of the panel) seem to be somewhat more similar to each other than the deciduous species, but this is difficult to address statistically because of the varying length of the records. The most striking feature of the corresponding δ^{13}C chronologies is again the period of high values in the late 1940s, but also the generally increasing trends, most pronounced in last 50 years of the record in the 20th century (Figure 5b). The increase from 1950 onward, for instance, may be expressed as a linear increase with time (‰ change per decade). This increase varies considerably between the chronologies, from 0.07‰/decade for *FS*-Bet, to 0.11‰/decade (*FE*-Bet), 0.14‰/decade (*QP*-Tic), 0.15‰/decade (*AA*-Bet), 0.19‰/decade (*FS*-Twa), 0.24‰/

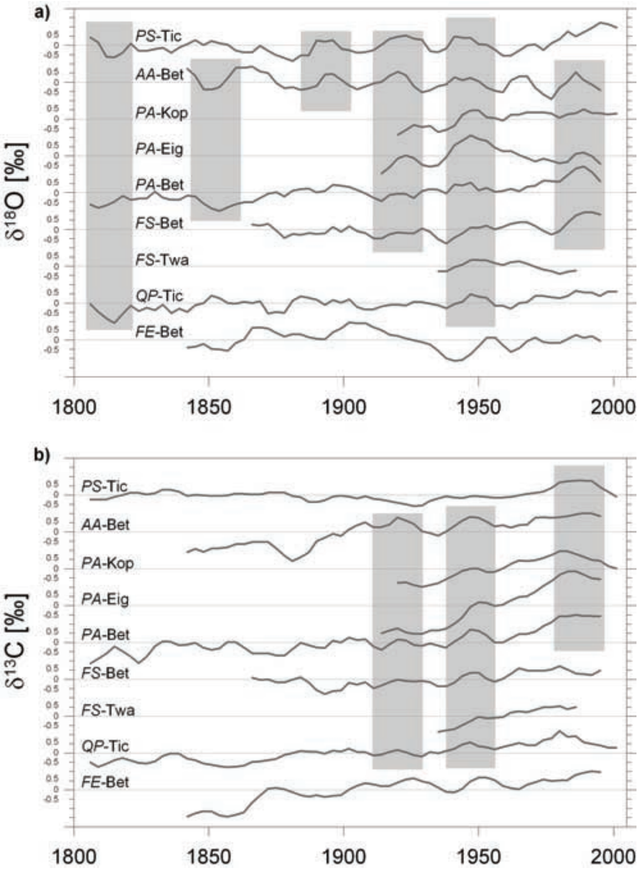

Figure 5. Nine-year running averages of the (a) oxygen and (b) carbon isotope chronologies. The data are shown as anomalies. The shaded areas highlight periods of common variability between the sites. Carbon isotope values were corrected for the change in δ^{13}C of atmospheric CO_2.

decade (*PA*-Kop), 0.27‰/decade (*PS*-Tic), 0.36‰/decade (*PA*-Bet), and to 0.49‰/decade (*PA*-Eig). In the most recent years, there seems like a maximum reached with values starting to decline slightly. Overall, there are fewer decadal-scale similarities between the records for δ^{13}C compared to δ^{18}O, in particular in the 19th century.

3.6. Composite Curves

[18] The generally good agreement between the sites as shown above makes it promising to investigate the climatic content of the composite curve of all sites over the full study range from 1803 to 1998. For this analysis, the 9-year running averages presented in Figures 5a and 5b are used and an average curve calculated (as described in "Data analysis"). The composite δ^{18}O curve is closely related to the annual temperature (Figure 6), as also confirmed by correlation analysis (Table 2), showing that decadal-scale oxygen isotope variability contains a useful climatic signal. Despite the reduced degree of freedom due to the smoothing, significant relationships are observed for annual as well as May–August and July–August temperatures. There is no obvious improvement with increasing number of chronologies contributing to the average. Apparently, the cool summer temperatures around 1815 are well reflected during a period when only 3 chronologies were available. Correlations to temperature are higher than for precipitation for the composite curve (Table 2). The average δ^{13}C chronology shows a very pronounced increase in the course of the 20th century (Figure 6), but also an increase over the full time period, which seems to be exaggerating the temperature increase. The standard error of the curve is also increasing over time because of a divergence in the strength of this 20th century increase in the different chronologies (see Figures 5b and 6). An additional difficulty is the reduced number of series available after 1995. There is a significant correlation of the δ^{13}C chronology observed with annual temperatures, but the decadal-scale fluctuations appear to be not as well preserved in the carbon compared to the oxygen isotope chronology.

4. Discussion

[19] The investigated sites have in common that tree growth is not limited by one single factor. Regarding tree ring width, such sites are usually characterized by a low degree of common variability between trees, a low correlation of the average chronology to climate and a low correlation to other similar sites [*Schweingruber*, 1988]. Nevertheless, the high-frequency isotope signal of the investigated sites is similar at all sites, as reflected in the high number of significant intersite correlations (see Figure 1). This holds even when chronologies built from different species are compared, whether gymnosperm or angiosperm. A similar observation was made by [*Hemming*

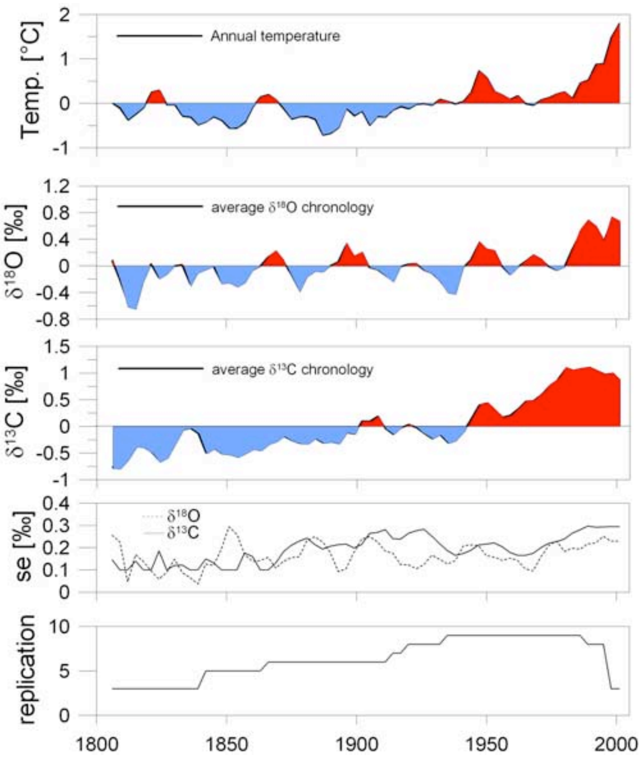

Figure 6. Composite curves showing 9-year running means of annual temperature anomalies, average δ^{18}O chronology, average δ^{13}C chronology and the number of chronologies contributing (replication). The standard error (se) of the isotope chronologies is also shown.

Table 2. Linear Regression Coefficients (*r*) Between the Composite Isotope and Climate Curves for the Period 1803 to 1998[a]

	Annual Temperature	May–Aug Temperature	July–Aug Temperature	Annual Precipitation	May–Aug Precipitation	July–Aug Precipitation
δ^{18}O	**0.73**	**0.55**	**0.63**	−0.14	−0.39	−0.40
δ^{13}C	**0.65**	0.25	0.43	−0.14	−0.30	−0.41

[a] The isotope chronology was calculated as the average of all chronologies, adjusted for offsets, on the basis of 9-year running averages. The climate data set was calculated as the average of two grid cells covering the area north of the Alps and one grid cell covering the southern part. Significant correlations are bold ($p < 0.05$).

et al., 1998] regarding δ^{13}C, where beech (*Fagus sylvatica*), oak (*Quercus robur*) and pine (*Pinus sylvestris*) showed similar variability at a site in central England. Correlations between chronologies of different species from one particular site (Bettlachstock) are in the same range as intersite correlations. The notable exception to the good correlations between the chronologies is *FE*-Bet which is not related to any other chronology, neither from the same site nor any other site, for both isotopes. As the climatic information in the *Fraxinus* series is also different from the other species (virtually absent for oxygen isotopes), differences in the physiology of this species compared to the other species could be important. Regarding δ^{18}O, this could e.g., be a difference in the water uptake, where a variable contribution of surface water versus water from deeper layers could obscure the signal (*Fraxinus* is a deep-rooting species). Differences in the gas exchange characteristics or phenology (relatively late date of bud break) might also play a role. As observed in [*Hölscher*, 2004], *Fraxinus* was described as the species with the highest maximum photosynthetic capacity of 8 cooccurring species in a broad-leaved mixed forest in Germany, but also the species with the lowest leaf area index. *Fraxinus* grows well as a pioneering species, but is not very shade-tolerant and photosynthesis may often be strongly limited under competition in an adult forest. Overall, the deviating isotope response of *Fraxinus* provides a cautionary note indicating that not all species may be equally well suited for palaeoclimate purposes.

[20] However, the generally high similarity of the isotope chronologies suggests climate as an important common driving force. The correlation analysis with climatic data provided results that are consistent with expectations from theory and with results from previous studies, namely (1) Positive correlations with temperature and negative correlations with precipitation for both isotopes [*Treydte et al.*, 2007] and (2) Strongest signal for growing season or summer climate [e.g., *Masson-Delmotte et al.*, 2005; *Schleser et al.*, 1999]. For oxygen, the positive correlation with temperature reflects the influence of the isotope signal of precipitation as the latter is known to be strongly determined by temperature [*Dansgaard*, 1964]. Precipitation amount may have an influence on δ^{18}O in tree rings via the effect on leaf water enrichment because wet climatic conditions (high precipitation) are associated with increased relative humidity, which in turn result in lower leaf water enrichment (thus the negative correlation) [*Edwards and Fritz*, 1986; *Roden and Ehleringer*, 1999]. Moreover the signal might depend on the timing of the highest water supply which could also result from snowmelt in regions with precipitation maxima in winter/spring [*Treydte et al.*, 2006]. In the analysis with annual resolution during the common calibration period, the strength of the correlation is similar for δ^{18}O with temperature and δ^{18}O with precipitation (Figure 2). However, the correlation with temperature is clearly stronger regarding the decadal-scale variations over the full record (Table 2). This result may indicate that extreme drought events may be well recorded in δ^{18}O, whereas subtle long-term changes in precipitation may be more difficult to reconstruct. On the other hand, there is no doubt that there is always a combined signal of temperature and precipitation in the oxygen isotope ratio preserved, which may accordingly lead to a high correlation with drought indices [*Treydte et al.*, 2007]. The information obtained from δ^{18}O is not strictly related to late summer (July–August), but rather captures a growing season or even annual signal (Figure 2). A pure latewood signal was analyzed only for the Bettlachstock site (whole rings for the other sites), but it is not obvious that the chronologies from the Bettlachstock site would be related rather to summer than to annual temperatures. Precipitation accumulating in the soil over some months may explain the relatively long (seasonal) time period revealed in the δ^{18}O signal. Our results further suggest that chronologies built from whole rings or latewood only retain similar climatic information.

[21] The observed correlation coefficients are not particularly high (on the order of $r = 0.5$). It should be noted, however, that an analysis of the data with local meteorological stations and the use of more detailed climate parameters may lead to higher correlations. For instance, for the *AA*-Bet oxygen isotope chronology, [*Rebetez et al.*, 2003] observed $r = 0.82$ for the correlation with the maximum temperature on rainy days for a local meteorological station, while we only report $r = 0.26$ here for the correlation of mean July–August temperature to the gridded climate data. The scope of this investigation, however, is rather to derive a regional climate signal and therefore the focus is on the common monthly temperature and precipitation values. Furthermore, stronger relationships to climate were actually observed for the combined series of all chronologies.

[22] Regarding the relationship between climate and carbon isotopes, drought conditions (i.e., high temperature/low precipitation) are known to result in lower stomatal conductance and lower isotope discrimination and ultimately in higher tree ring δ^{13}C [*Farquhar et al.*, 1982; *Leavitt and Long*, 1989; *Saurer et al.*, 1995]. Looking at the results of the correlation analysis (Figure 3), this response pattern is confirmed for most of the chronologies, with similar strength of the correlations obtained for summer, growing season or annual data. However, the investigated sites are in an area of temperate climate and accordingly not under a strong limitation by water stress. The observed carbon isotope response to warm-dry conditions may therefore not only be a stomatal signal, but may also reflect

changes in assimilation rates. A closer look at the correlations in the 20th century by a moving window technique showed a remarkable decline in the climate-isotope relationship during the last 3 decades (Figure 4). Except for *Fraxinus*, the *r*-values between δ^{13}C and July–August temperature are clearly more positive in the first part of the century compared to the period after about 1960. This decline in the climate signal is similar to the so-called divergence observed for tree ring width and density, a postulated reduced sensitivity of the trees to climate in recent decades [*D'Arrigo et al.*, 2008]. But the decline in the correlation observed in our study also coincides with an accelerated increase in atmospheric CO_2 concentration [*Francey et al.*, 1999]. CO_2 has a direct effect on gas exchange as is known from many CO_2 enrichment experiments, where an increase in the intrinsic water use efficiency (iWUE) due to reduced stomatal conductance and increased photosynthesis was often observed [*Drake et al.*, 1997; *Körner*, 2000]. Such an increase in iWUE was also deduced from many tree ring studies by applying the Farquhar model of isotopic discrimination [e.g., *Bert et al.*, 1997; *Waterhouse et al.*, 2004]. It therefore seems possible that the reduced correlation between carbon isotope variations and temperature in our study is related to a response to the steep increase in atmospheric CO_2 concentration, while other explanations such as changing nitrogen deposition cannot be ruled out completely. It is further noteworthy that we observe strongly diverging δ^{13}C trends in recent decades. A variable response is found, in particular, for the different *Picea abies* chronologies, similar to what was already noted in [*Saurer et al.*, 2004b]. This divergence also results in an increase in the standard deviation in the combined δ^{13}C record. Provided that δ^{13}C is indeed influenced by a direct CO_2 effect, independent of climatic influences, this poses some serious problems for the calibration of δ^{13}C to climatic data. It was suggested that a correction for the CO_2 effect might be applied, but the nature of such a correction still is unclear, because it would be site- and species-dependent [*Feng and Epstein*, 1995; *Treydte et al.*, 2001] (D. McCarroll, personal communication, 2008). Our data might suggest as an alternative way to minimize the problem by not using the last 3 or 4 decades for the calibration, because an accelerated CO_2 effect is observed in this period and a corresponding decline in the correlation strength. Similarly, [*Briffa et al.*, 2002] calibrated regional reconstructions in the Northern Hemisphere against pre-1960 instrumental observations because of a nontemperature signal in the maximum latewood data in recent decades. However, omitting this period did not significantly improve climatic correlations in our study, because the observed increase in temperature is still well reflected by the overall δ^{13}C increase in recent decades, despite the high uncertainty in the δ^{13}C curves.

[23] We observed that the climate-isotope relationship generally improves when the average of several chronologies is considered (Figures 3a and 3b). This trend is most pronounced for oxygen for the correlation with temperature and precipitation, while for carbon it is only observed for the correlation with temperature, but not with precipitation. This improvement by averaging might be expected on the one hand, because the different chronologies show overall similar responses to climate, but is still surprising in view of the wide range of different site conditions and different species considered and the temperate climate at the lowland sites investigated. It should be recalled that also a divergent chronology like *Fraxinus* was included in the average. Concerns were raised recently on the stability of the climate-isotope relationship at nonextreme sites [*Reynolds-Henne et al.*, 2007]. Our study indicates that combining several species may improve the reliability of the reconstruction by cancelling out some of the biological noise. The results from Figures 5 and 6 show that a reliable decadal-scale signal can be retrieved from nondetrended isotope data, in particular for oxygen. The uncertainty in the first part of the combined record probably is higher because of fewer chronologies being available in the 19th century, but a correlation coefficient of 0.73 for oxygen and 0.65 for carbon is found for the correlation between annual temperatures and isotopes for the total record length.

[24] When comparing the climate-isotope relationships for carbon and oxygen, the general observation from the correlation analysis is that rather similar information is contained in the two isotopes. This means that despite different processes being responsible, ultimately temperature and precipitation changes affect the two isotopes in a similar manner (e.g., high temperature/low precipitation resulting in increased isotope values). It therefore seems plausible that combining the information of such proxies would increase the climate signal [*Gagen et al.*, 2006]. Indeed, when applying a multiple linear regression with δ^{13}C and δ^{18}O as variables, the resulting correlation coefficients are somewhat higher compared to the simple regression coefficients and vary less between species. This could indicate that at least for temperate sites a more reliable climate reconstruction is possible when combining the two isotopes.

5. Conclusion

[25] Our results indicate a large benefit to be achieved by combining tree ring isotope series from temperate sites, even for studies originally designed for different purposes, chronologies constructed for different species, and samples that have been differently processed (latewood versus whole years, cellulose versus whole wood). We have shown that combining several chronologies produces a more reliable climate reconstruction by averaging out biological differences and is promising also in view of networks and databases of isotope series being currently developed. From the six investigated species, we could identify five as equally well suited for climate reconstruction. The results may also have some significance for the use of historic wood where one is faced with the problem of unknown provenance and site ecology [*Wilson et al.*, 2005]. Our results indicate generally significant correlations between chronologies in an area of approximately 100 km × 150 km, some sites even separated by the Alpine mountain ridge, therefore much larger areas of significant correlations might be expected on topographically less complex terrain. We observed strong coherence between high-resolution carbon isotope records, whereas decadal-scale variations were more similar for the oxygen records. The averaging produced more successful results for temperature than for precipitation. We mostly considered each isotope separately, but a

combination of the two might further enhance the climate information: if two proxies share similar controlling factors but have different physiological controls, combining their estimates should cancel out some of the noise. Our results reinforce the important role of isotopes for unbiased long-term climate reconstructions of temperature and precipitation for nonlimited lowland sites.

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W. T. Anderson, Earth Sciences Department and Southeast Environmental Research Center, Florida International University, Miami, FL 33199, USA.

P. Cherubini and K. S. Treydte, WSL Swiss Federal Research Institute, CH-8903 Birmensdorf, Switzerland.

C. E. Reynolds-Henne, Institute of Plant Sciences, University of Bern, CH-3013 Bern, Switzerland.

M. Saurer and R. T. W. Siegwolf, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland. (matthias.saurer@psi.ch)