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Short Communication

Larix decidua $\delta^{18}O$ tree-ring cellulose mainly reflects the isotopic signature of winter snow in a high-altitude glacial valley of the European Alps

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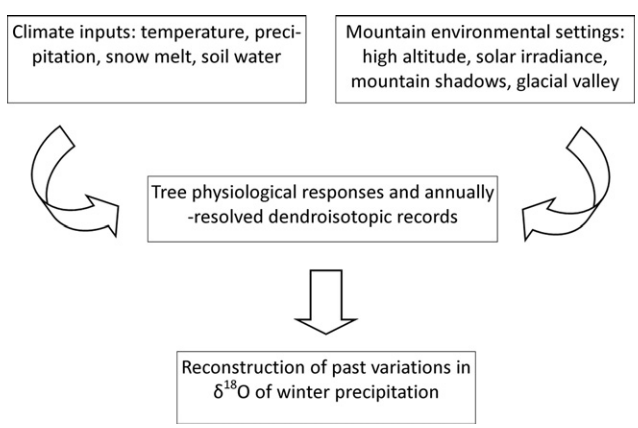
HIGHLIGHTS

- A dendroclimatic study was set up in a neo-deglaciated valley of the European Alps.
- Chronologies of tree-ring cellulose stable isotopes ($\delta^{13}C$ and $\delta^{18}O$) were analyzed.
- The $\delta^{18}O$ of tree-ring cellulose was strongly driven by the $\delta^{18}O$ of winter snowfall.
- The $\delta^{18}O$ chronology explained up to 34% of the winter precipitation $\delta^{18}O$ variability.
- Tree rings potentially allow the reconstruction of past winter precipitation $\delta^{18}O$.

GRAPHICAL ABSTRACT



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ABSTRACT

We analyzed the chronologies of cellulose stable isotopes ($\delta^{13}C$ and $\delta^{18}O$) and tree-ring widths from European larch (*Larix decidua*) in a high-altitude site (2190 m a.s.l.) at the bottom of a glacial valley in the Italian Alps, and investigated their dependence on monthly meteorological variables and $\delta^{18}O$ precipitation values. The $\delta^{18}O$ of tree-ring cellulose appears to be strongly driven by the $\delta^{18}O$ of winter snowfall (November to March), which suggests that larch trees mostly use the snow-melt water of the previous winter during the growing season. This water, which also comes from the slope streams and from the underground flow of nearby steep slopes, infiltrates the soil in the valley bottom. The tree-ring cellulose $\delta^{18}O$ values were also found to be influenced by the August precipitation $\delta^{18}O$ and mean temperature. The associated regression model shows that the $\delta^{18}O$

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chronology from the tree rings explains up to 34% of the variance in the winter precipitation $\delta^{18}O$ record, demonstrating the potential for reconstructing the $\delta^{18}O$ isotopic composition of past winter precipitation in the study region. Unlike most other tree-ring studies that focus on growing season signals, in our study the summer signal was small and the winter signal dominant due to the special conditions of the glacial valley. Site topography, geomorphology and soil characteristics in particular influence the stable isotope signal in tree-ring cellulose.

1. Introduction

Reconstructions of global and regional climates during pre-instrumental periods are often based on tree-ring proxies linked to cambial activity and biomass accumulation, such as ring-width or maximum-latewood-density (e.g., Briffa et al., 2002; Luterbacher et al., 2016). Past summer temperatures in the European Alps have been reconstructed using chronologies hundreds to thousands of years long (e.g., Büntgen et al., 2005, 2011; Casty et al., 2005; Corona et al., 2010; Coppola et al., 2013; Leonelli et al., 2016) as have, more rarely, past precipitation regimes (e.g., Strumia, 1999; for Central Europe: Wilson et al., 2005; Büntgen et al., 2009).

In recent years, the possibility of using tree-ring stable isotopes for reconstructing past climate variability has received increasing interest because their sensitivity to climate is strictly controlled by the environmental conditions impacting tree physiology. These isotopes may provide additional climatic information that cannot be derived from the classical tree-ring proxies related to tree growth typically used in dendroclimatology (Gessler et al., 2014). Moreover, tree-ring stable isotopes potentially allow strong climatic signals to be captured even from temperate forest sites and not only from climatically stressed sites such as those at high altitudes (Saurer et al., 2000, 2008), with near uniform variation in stable isotopes across sites, species (Hartl-Meier et al., 2015) and elevation (Treydte et al., 2001). The variability in stable isotope signatures stored annually in wood and cellulose is linked to trees' physiological responses to environmental conditions, meteorological variables and site characteristics. The tree-ring stable isotope response to climate may also be affected by geomorphological conditions, particularly soil water availability, which may vary greatly within small distances since alpine environments tend to be highly heterogeneous (Leonelli et al., 2014a).

The variability of $^{18}O/^{16}O$ in tree-ring cellulose depends on several factors including: — the isotopic signature of the source water, which, in turn, varies with i) seasonal precipitation, ii) soil-water profile, and iii) rooting depth; — iv) the leaf-water enrichment during transpiration, and — v) the post-photosynthetic exchange rates of oxygen of the assimilates with the xylem water during wood synthesis and biomass accumulation (in the corresponding trunk fractions). The seasonality of $\delta^{18}O$ in precipitation (i) is due to the temperature dependence of the oxygen isotope ratio in rain during the condensation of cloud water (Dansgaard, 1964). The declining water isotope profile in the soil (ii) is caused by the infiltration of rain and snow water during the cool seasons (fall and winter), whereas during summer it is enriched because considerable amounts of precipitation evaporate from the soil surface (Saurer et al., 2016). Consequently, the source water of trees is a mixture of the water collected by the roots at different soil depths, which is why $^{18}O/^{16}O$ in tree-ring cellulose also depends on the rooting depth (iii). Leaf-water enrichment (iv) occurring during photosynthesis and transpiration (Barbour, 2007; Cernusak et al., 2016) usually amplifies the oxygen signal contained in the rain water. Thus we find the leaf water is most enriched when it is warm and transpirative demands are high. Whether we find an amplification or not depends on the rooting depth where the trees collect their water.

The $\delta^{18}O$ enrichment in leaves, and thus that of the assimilates, is mainly driven by the partial pressure ratio of water vapor between the ambient air and the leaf internal spaces (~RH) (Dongman, 1974; Roden et al., 2000). The strength of the climatic signal driven by the source water signature, with respect to the signal linked to the enrichment processes at the leaf level, is further impacted by the post-photosynthetic exchange rates (v) of oxygen with the xylem water during wood synthesis and biomass accumulation in the trunk (Roden et al., 2000; McCarroll and Loader, 2004). The site's orographic conditions and soil properties influence whether the variations in source water $\delta^{18}O$ have more effect than needle water enrichments (Treydte et al., 2014). Larch trees in glacial environments of the Alps are highly sensitive to $\delta^{18}O$ changes in the soil water induced by glacier melting water, which is why the analysis of cellulose $\delta^{18}O$ chronologies can also be used for dating and reconstructing past glacier runoff events (Leonelli et al., 2014b).

The isotopic signature of precipitation in Southern Europe and the W-E and N-S gradients of $\delta^{18}O$ depend on atmospheric circulation dynamics, with precipitation increasingly ^{18}O-depleted further away from the Atlantic Ocean and the Mediterranean Sea. Moreover, the isotopic altitudinal gradient of approximately −0.2‰/100 m observed in mountain environments (Longinelli and Selmo, 2003) strongly influences the $\delta^{18}O$ signature of precipitation. Other factors influencing the $\delta^{18}O$ of precipitation at the local scale are the "shadow" effect of the surrounding mountains, which may also induce an inversion of the commonly negative isotopic altitudinal gradient, as well as changes in the annual distribution of precipitation, which may influence the annual $\delta^{18}O$ values (Longinelli et al., 2006).

The variability of the $^{13}C/^{12}C$ ratio in tree ring cellulose is mainly controlled by photosynthesis and stomatal conductance. At dry sites these processes depend mostly on the air humidity and soil water availability (Farquhar et al., 1989), whereas at moist sites the C-isotope ratio reflects the variability of summer irradiance and temperature (Panek and Waring, 1997; Leffler and Evans, 1999; McCarroll and Loader, 2004; Seibt et al., 2008).

Both $\delta^{13}C$ and $\delta^{18}O$ chronologies are very sensitive to environmental conditions, which is why they have been used for reconstructing different climatic parameters according to the strength of the established relationships. Tree-ring chronologies of $\delta^{13}C$ have been analyzed to find out more about the impact of summer drought at dry Mediterranean sites (De Micco et al., 2007; Di Matteo et al., 2010; Tognetti et al., 2014; Altieri et al., 2015), as well as to reconstruct past droughts and summer moisture availability in the European Alps (Kress et al., 2010). They have been related to atmospheric humidity and soil moisture, with stronger signals at lower elevations and relatively dry sites (Saurer et al., 1995; Treydte et al., 2001), where lower stomatal conductance may induce higher sensitivities (Saurer et al., 2014; Gessler et al., 2014). Tree-ring chronologies of $\delta^{18}O$ have been used in analyses of the $^{18}O/^{16}O$ ratio of precipitation over the whole Eurasian latitudinal treeline (Saurer et al., 2002, 2016) and reconstructions of past precipitation variability in northern Pakistan (Treydte et al., 2006).

In this paper, we analyzed the paleoclimatic potential of European larch tree-ring cellulose stable isotopes from an inner Alpine glacial valley to: i) quantify the influence of meteorological variables (i.e., precipitation and temperature) on tree-ring growth and ii) evaluate how much monthly meteorological variables affect the variability of stable C and O isotopes in cellulose, and how much the monthly/seasonal averages of $\delta^{18}O$ of precipitation affect the $\delta^{18}O$ of cellulose.

2. Materials and methods

2.1. Site location, tree-ring width and stable-isotope chronologies

The study site is located in the Forni Valley (Upper Valtellina, Italian Alps) in the inner part of the Alpine range (Fig. 1A; Lat. 46°25′5.45″N; Long. 10°33′57.92″E) at approximately 2190 m a.s.l. The site is on a gentle slope at the bottom of the U-shaped glacial valley of the Forni Glacier (the largest valley glacier in Italy). Mica-schist and paragneiss of the Pejo Unit characterize the lithology of the area (Argenton et al., 1980). The poorly developed soils reflect the site's recent pedologic evolution following the still ongoing glacial retreat from the valley floor, which started after the end of the Little Ice Age (approximately 1850 CE; Pelfini et al., 2014). The ground surface at the study site became free from the glacier body between 1914 and 1926 CE, and the first surviving trees germinated approximately 55 years after the initial soils developed (unpublished data). The shallow soils in the valley floor, which can be defined as rankers (Duchaufour, 1983), are approximately 15–30 cm deep, and present A and stony C horizons with a high abundance of gravel (between approximately 40%–50% in A and C horizons) and an acidic pH (5–5.9).

The study site is affected by air masses with different origins. It is approximately 900 km East of the Atlantic Ocean, 270 km North-East of the northern Tyrrhenian Sea and 190 km North-West of the Adriatic Sea, which means it is sometimes affected by the humid air masses traversing the Alps from the South. The $\delta^{18}O$ of precipitation ranges from −14.42‰ (mean of the months with air temperature < 0 °C: November to March) to −8.67‰ (mean of the mid-late summer months: July to September) according to the University of Utah's 3D model (http://wateriso.utah.edu/waterisotopes/index.html).

Five European larch (*Larix decidua* Mill.) trees were sampled in summer 2011 with two cores per tree taken at 1.3 m above ground. Transversal surfaces were prepared for each core with a razor blade and the tree-rings counted and measured to the nearest 1/100 mm using a LINTAB system connected to a computer with the TSAP software (both RINNTECH, Heidelberg, Germany). The age trend was removed from the individual raw series fitting a cubic spline 2/3 the series length and calculating the growth indices as ratios between the measured and modeled values. The standard chronology for the site was then obtained by applying a robust bi-weight mean to reduce the influence of outliers and enhance the common signal (Cook et al., 1990). The cores were then cut with a razor blade by separating each dated tree ring from the core for the period 1980–2010. All tree rings from the same year but different cores were then pooled together and milled to a powder < 0.05 mm in diameter. The α-cellulose was extracted according to the method described in Loader et al. (1997).

We weighed 0.5–0.7 mg of cellulose in silver capsules to determine $\delta^{18}O$ and 0.6–0.8 mg in tin capsules to determine $\delta^{13}C$. The ^{18}O and ^{13}C isotope ratios were measured in WSL's laboratories with an isotope ratio mass spectrometer (IRMS) and the samples were treated with pyrolysis and combustion, respectively. Since we found two anomalous $\delta^{18}O$ values in the first analysis run, we decided to validate this series by re-measuring some tree rings using IRMS in a different lab, the CIRCE Lab (Center for Isotopic Research on the Cultural and Environmental Heritage, Second University of Naples, Italy. A total of 5 tree rings, including the two anomalous values were re-measured, and the new values were based on the mean differences between the two laboratories (0.078‰). The $\delta^{13}C$ series were corrected for changes in the $^{13}C/^{12}C$ of the atmospheric CO_2 associated with fossil fuel combustion, which causes a decrease in $\delta^{13}C$. This decrease is transferred to the organic material. We therefore corrected the $\delta^{13}C$ of in the tree cellulose according to Francey et al. (1999).

2.2. Meteorological data and precipitation $\delta^{18}O$ series

Records of monthly mean temperature and total precipitation for the period 1980–2010 were obtained for the study site from both a local station (which only partially covers the period considered), and stations at Bormio and Santa Caterina Valfurva, 6.5 and 16.5 km west of the study site, respectively (Fig. 1A). All meteorological records were processed with standard homogenization techniques, and the

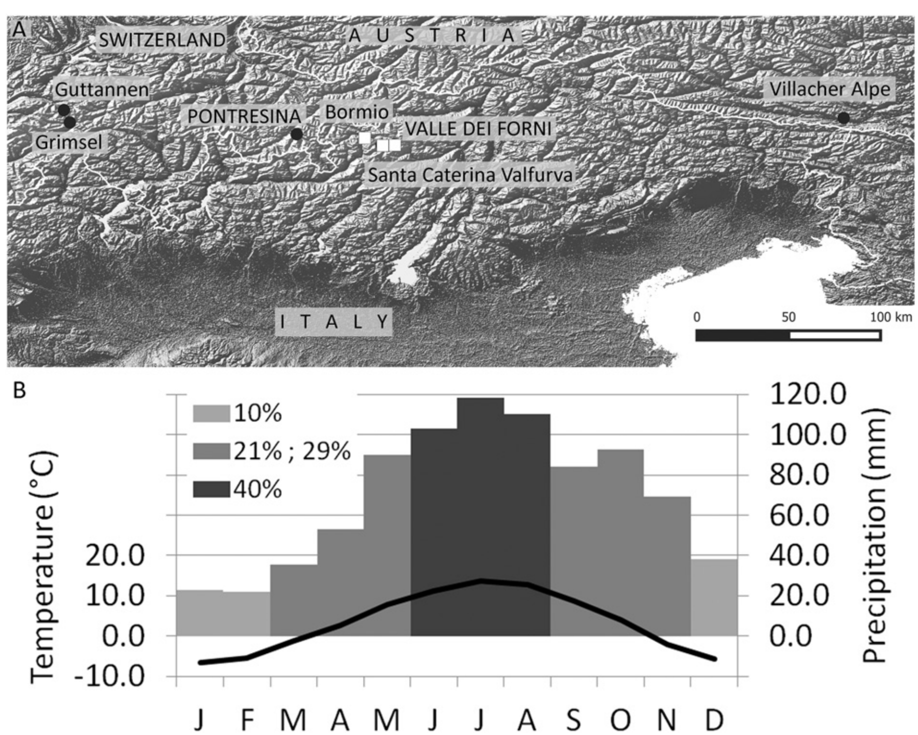

Fig. 1. A. Location of the Valle dei Forni study site and the stations used for climate data (white squares) and precipitation $\delta^{18}O$ (black dots). B. Climate diagram of the Forni-reconstructed monthly series showing mean temperature and mean precipitation sum over the period 1980–2010.

different records merged taking into account the different means and variability of each station (Brunetti et al., 2009).

The mean annual temperature is low (3.3 °C) due to the high altitude of the site (Fig. 1B), varying greatly with season. A daily mean temperature of 5 °C is the critical value below which tree growth is strongly limited (Tranquillini, 1979; Körner, 2003; Körner et al., 2016), and is usually exceeded at the site between May and September. Annual precipitation is approximately 850 mm, with 40% falling from June to August and 10% falling from December to February (Fig. 1B). During the months with a mean temperature below 0 °C (i.e. November to March), precipitation mostly falls as snow. Occasionally, it may also snow during summer.

The $\delta^{18}O$ series of monthly precipitation of the nearby station in Pontresina (approximately 50 km west of the study site, in Switzerland) was sourced from the Global Network of Isotopes in Precipitation (GNIP; IAEA/WMO, 2016). Since this series has some gaps and only began in July 1994, we supplemented it with the GNIP series from the Guttannen and Grimsel stations in Switzerland, and the Villacher Alpe station in Austria. These are the closest high-altitude stations (>1000 m a.s.l.) in the European Alps available and are at most 200 km away from the study site (Fig. 1; Table 1).

All isotopic chronologies had similar mean annual and seasonal values, and the series of mean annual $\delta^{18}O$ values at the different stations always correlated significantly over the respective common periods. Pontresina is the closest station to the study site, and its $\delta^{18}O$ time series is the most representative for this study. Moreover, it has similar climatic conditions to those at the study site, with the same monthly temperature regime, while its monthly precipitation record correlated highly with that of the Forni Valley (Table 1, bottom).

2.3. Correlation analysis

Correlations between the tree-ring data (ring-width and $\delta^{13}C$, $\delta^{18}O$ stable isotope chronologies) and the (monthly) mean temperatures, total precipitation and (monthly and seasonal) precipitation $\delta^{18}O$ were measured over the 31-year period 1980–2010. To account for the possible effect of previous-year meteorological variables on growth (Fritts, 1976), Pearson's correlation coefficients were calculated from June of the year prior to growth to September of the year of growth. Based on the correlation analysis results, a linear regression model was then calibrated to estimate the $\delta^{18}O$ of precipitation from the $\delta^{18}O$ of tree-ring cellulose.

3. Results and discussion

The correlation analysis revealed that, of all the variables analyzed, the $\delta^{18}O$ of January precipitation had the most influence on the cellulose $\delta^{18}O$ (Fig. 2). In regard to the ring-width index (Fig. 2A), tree-ring growth appears to be enhanced by high summer temperatures (max $r_{July} = 0.41$; $p < 0.05$), as well as by warm winters prior to growth (max $r_{December-1} = 0.4$; $p < 0.05$). Precipitation during summer (the wettest period of the year) tends to negatively affect tree-ring growth at the beginning of the season (max $r_{July} = -0.43$; $p < 0.05$), whereas it enhances growth towards the end of the season (max $r_{August} = 0.37$; $p < 0.05$), a positive influence that lasts also in the following year's growth (variable $September_{-1}$).

To evaluate the influence of temperature and precipitation on the stable isotope composition of the tree-ring cellulose, the dual $\delta^{13}C$ and $\delta^{18}O$ approach proposed by Scheidegger et al. (2000) was used to interpret the physiological mechanisms responsible for the isotopic variability in organic matter. This should make it easier to evaluate the interplay between stomatal conductance and photosynthesis in a plant. However, this model is best applied to organic matter synthesized at the leaf level and does not relate as tightly to wood in plants (Roden and Siegwolf, 2012), nor does it take into consideration issues such as the spatial variability of $\delta^{18}O$ in source water and the post-photosynthetic synthesis of wood cellulose, which dampens the $\delta^{18}O$ signal in the leaf organic matter (Gessler et al., 2014).

We found a negative correlation between June temperatures and $\delta^{13}C$ (Fig. 2B). This was rather unexpected since high temperatures in this month should increase the vapor pressure deficit (VPD) and increase the transpirative demand, resulting in a reduction of stomatal conductance. Reduced conductance should then, according to Scheidegger et al. (2000), lead to an enrichment of cellulose with both ^{13}C and ^{18}O. We found, however, that higher temperatures cause a decrease in $\delta^{13}C$ and no response in $\delta^{18}O$ in June (Fig. 2C). This could be the result of more water becoming available as the snow and ice typically found in mountainous regions melt. Consequently, the soil may become anaerobic, water uptake disturbed and photosynthesis impaired. In August, high temperatures tend to induce a decrease in stomatal conductance, and tree-ring growth is controlled by precipitation rather than temperature. This corresponds well with Treydte et al.'s (2001) findings along an alpine treeline at approximately 2000 m a.s.l. in the Lötschental, Swiss Alps: during the growing season, $\delta^{13}C$ was poorly (and at one site also negatively) correlating with temperatures in

Table 1
Station characteristics of the GNIP network (IAEA/WMO, 2016; A = Austria, CH = Switzerland) selected to reconstruct the $\delta^{18}O$ series of Pontresina compared with the tree-ring cellulose $\delta^{18}O$ at the Forni Valley study site. The mean $\delta^{18}O$ values at the stations, as well as the correlations between the series of $\delta^{18}O$ and precipitation sums, were calculated for the maximum periods available. For precipitation, only the comparison of the reconstructed Forni series (IT = Italy) with the Samedan (CH) series is reported.
$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; WINTER (November-1 to March); SUMMER (May to September); NA = data not available for the series overlap.

Station	Period 1995–2002 (N = 8)				
	Altitude [m a.s.l.]	First–last year available	Mean annual $\delta^{18}O$ [‰]	Mean WINTER $\delta^{18}O$ [‰]	Mean SUMMER $\delta^{18}O$ [‰]
Villacher Alpe – A	2156	1973–2002	−10.59	−12.74	−8.55
Grimsel - CH	1950	1971–2014	−13.32	−15.98	−10.81
Pontresina - CH	1724	1995–2014	−13.66	−18.24	−9.34
Guttannen - CH	1055	1971–2014	−12.11	−15.03	−9.24

r on annual precipitation $\delta^{18}O$	Period 1973–2002 (N = 30)			Period 1995–2014 (N = 20)		
	Grimsel - CH	Guttannen - CH	Pontresina - CH	Grimsel - CH	Guttannen - CH	Pontresina - CH
Villacher Alpe - A	0.49^{**}	0.52^{**}	NA	NA	NA	NA
Grimsel - CH	–	0.91^{***}	NA	–	0.79^{***}	0.54^{*}
Guttannen - CH	–	–	NA	–	–	0.67^{**}

r on monthly precipitation sums $Forni_{reconstructed}$ - IT vs. Samedan - CH station (5 km NNE from Pontresina); values for 12 months	Period 1981–2015 (N = 35)
Mean (±1σ)	0.79^{***} (±0.12)
Max	0.92^{***} (November)
Min	0.50^{**} (December)

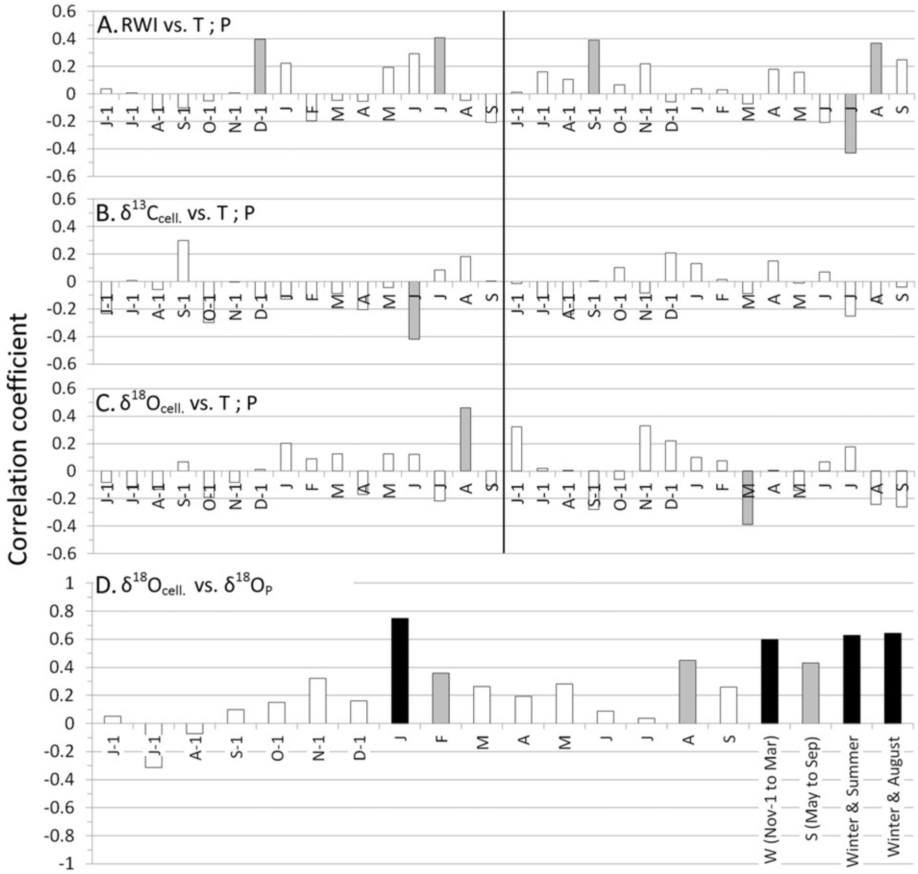

Fig. 2. Correlation coefficients calculated for monthly temperatures (T) and precipitation (P) from June of the previous year to September of the current year, with: A. the standardized ring-width chronology (RWI); B. the cellulose δ^{13}C chronology; and C. the cellulose δ^{18}O chronology. D. Correlations between the cellulose δ^{18}O chronology and the precipitation δ^{18}O of the Pontresina-reconstructed series, using monthly variables and their aggregations. Note the different scales of the y-axis. In all cases, white bars for correlation coefficient values depict statistically non-significant values; gray bars indicate significant values ($p < 0.05$); black bars indicate highly significant values ($p < 0.001$).

June, and positively correlating with temperatures in July and in August, while precipitation variables followed almost the same patterns as in our study, but we found lower absolute values.

Of the climate variables influencing cellulose δ^{18}O, we found that August temperatures had the strongest positive correlations, whereas precipitation had less impact (Fig. 2C). The δ^{18}O of precipitation had, however, a much higher explanatory power for the variability of δ^{18}O in the cellulose of European larch at our study site (Fig. 2D), with the δ^{18}O of winter precipitation having the strongest influence. This result is highlighted by the high correlation between the average precipitation δ^{18}O in the winter months and the tree-ring cellulose δ^{18}O ($r_{WINTER} = 0.60$; $p < 0.001$; where WINTER is defined as from November$_{t-1}$ to March$_t$). In contrast, the positive correlation between the δ^{18}O of precipitation and tree-ring cellulose δ^{18}O was lower in the summer months ($r_{SUMMER} = 0.43$; $p < 0.05$; where SUMMER is defined as from May$_t$ to September$_t$). The highest correlation of precipitation δ^{18}O with tree-ring cellulose δ^{18}O in the monthly records were found for January ($r = 0.75$; $p < 0.001$). The correlation between δ^{18}O of January precipitation and δ^{18}O of European larch cellulose Daux et al. (2011) found in the western European Alps was lower but still significant. A study of *Quercus robur* L. in east England (Robertson et al., 2001) reported even higher correlations ($r = 0.88$) between unweighted December–January precipitation δ^{18}O and the latewood cellulose δ^{18}O.

The positive relationship between the δ^{18}O of cellulose and precipitation is well known and can be explained by isotopic theory (Treydte et al., 2014). In most cases, however, the strongest relationships have been found for the growing season (see Saurer et al., 1997 for *Fagus sylvatica* L. from relatively dry sites in Switzerland and Danis et al., 2006 for *Q. robur* from the western Alps in France). In our case, the topographic and pedologic characteristics seem to drive the soil water replenishing times, along with the soil water residence times in the unsaturated zone. This influences the type of water that is then taken up during the growing season, which itself depends on the tree's physiological condition (e.g., rooting depth). This process is then reflected in the cellulose δ^{18}O.

The linear regressions of cellulose δ^{18}O on winter and summer precipitation δ^{18}O show similar slopes, but the regression error is much lower in winter (Fig. 3A). The δ^{18}O chronologies of tree-ring cellulose and precipitation in the period 1980–2010 show that a remarkable fraction of the δ^{18}O of WINTER precipitation can be captured during biomass production. This winter δ^{18}O signal is then reflected in the tree-ring cellulose (Table 2). The overall fraction of variance in the winter precipitation δ^{18}O explained by the model is 34%, and the estimated standard deviation of the "noise" that is not explained by tree-ring δ^{18}O, i.e., the standard error of the model, is 1.46 ($t = 2.05$; d.f. 29) (Fig. 3B). The error has a normal distribution, as reflected by the adjusted Anderson-Darling statistics (whose value is 0.27; $p = 0.69$; nonlinearity hypothesis rejected). The model tends, however, to slightly overpredict the δ^{18}O of precipitation in the early period (1980–1987). No autocorrelation is present in the residuals (lag 1 = 0.075; lag 2 = −0.127), and they are always <2.84‰ in absolute values.

Overall, at our study site we found that the isotopic signals of winter precipitation are more strongly reflected in the tree cellulose (in particular in the January signal) than the δ^{18}O of summer precipitation. In summer, the August temperatures have most effect on the cellulose δ^{18}O. This may indirectly cause the correlation with δ^{18}O of August

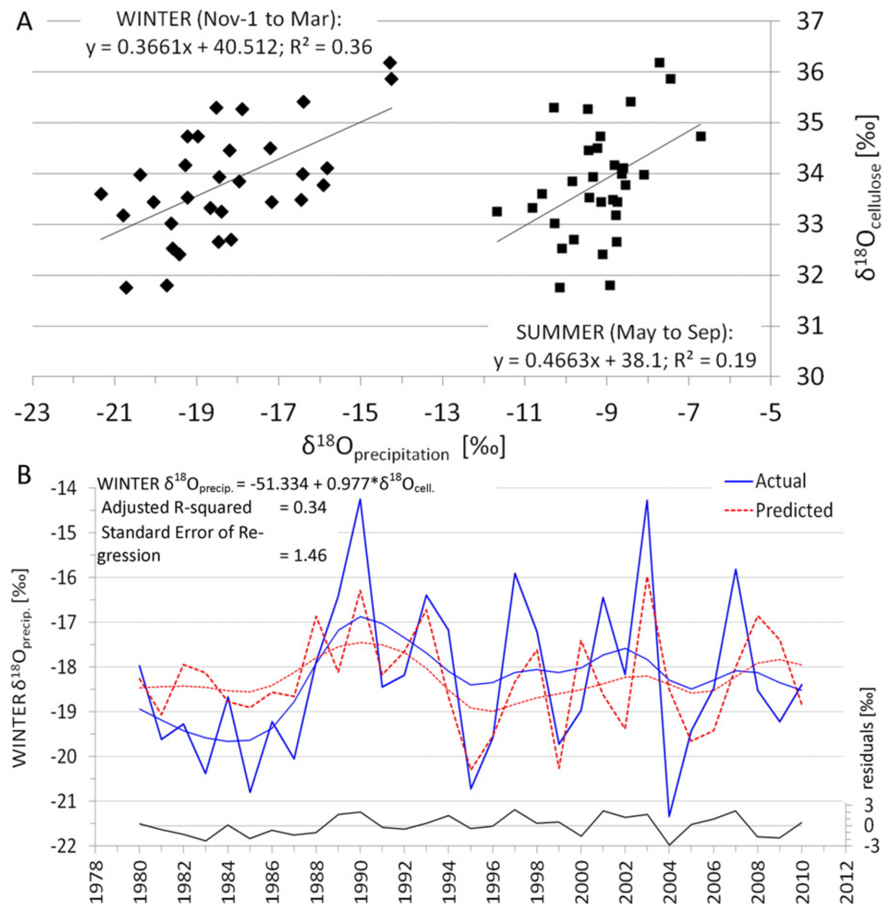

Fig. 3. A. Linear regression between the cellulose $\delta^{18}O$ and the precipitation $\delta^{18}O$ (Pontresina-reconstructed series) for the winter months (rhombuses) and the summer months (squares). For all regressions, the linear regression equation is reported, together with the corresponding equation and determination coefficient. B. Simple regression model calibrated for the period 1980–2010 to estimate the winter $\delta^{18}O$ of the Pontresina-reconstructed series based on the cellulose $\delta^{18}O$ chronology. Smoothed lines are Gaussian filters (15 y; $\sigma = 3$y), while the black line depicts the model residuals (difference between actual and predicted values). The regression equation is given together with the adjusted determination coefficient and the standard error of the model.

precipitation because the lower air relative humidity and the warmer conditions in summer may induce more evaporation and leaf water enrichment.

During the month of July, when most of the biomass in the tree-ring is produced at the study site, trees on the valley floor mainly take their water from snow melt that has infiltrated in the soil. The soil water is also continuously replenished by the streams, which collect melt water from the nearby steep slopes of the U-shaped glacial valley. Frozen ground at the beginning of the growing season could even promote nearly stagnant soil-water conditions because it slows down the gravitational movement of infiltration. The time when snow melt is present in the soil at the study site overlaps with the maximum tree-ring growth in July. Even though up to 40% of the total precipitation falls during the summer months, we find only a weak $\delta^{18}O$ signal for the August precipitation, which slightly influences the $\delta^{18}O$ in cellulose. This indicates that the precipitation signature from May, June and July is mostly lost

Table 2
Summary of the simple regression model for the WINTER $\delta^{18}O$ (1 variable, $n = 31$; d.f. 29): coefficient values of tree-ring $\delta^{18}O$ are reported together with the standard error, related t-statistics and 95% confidence intervals.

Variable	Coefficient	Standard error of the coefficient	t-Statistic	*p*-Value	Lower 95%	Upper 95%
Intercept	−51.334	8.226	−6.241	0.000	−68.158	−34.511
Tree-ring $\delta^{18}O$	0.977	0.243	4.020	0.000	0.480	1.475

with surface runoff, when the soil is still saturated with winter snow melt. During these months, precipitation, that is usually associated with lower air temperatures, inhibits tree-ring growth, possibly because the soil is then oversaturated and anaerobic conditions occur. By August most of the winter water that infiltrated has probably been washed out and the ground fully thawed, making the $\delta^{18}O$ signal of August and late summer precipitation available for tree growth, so that the summer $\delta^{18}O$ signal is incorporated in the cellulose.

The signals of the cellulose stable isotopes in earlywood and latewood were found to be similar in a study of different conifer trees growing at the treeline in the Alps (Kress et al., 2009). It is likely that, in cellulose from the study site, where the soil water signals recorded over the growing season months varied greatly, the winter signal in cellulose $\delta^{18}O$ could be enhanced more by separating the earlywood, formed mainly in June and July, from the latewood, formed mainly in August and September.

4. Conclusions

This study has shown that the $\delta^{18}O$ of European larch cellulose may be used as a proxy for past $\delta^{18}O$ of winter precipitation under the special site conditions found in the glacial valley we studied. The tree-ring $\delta^{18}O$ from the site correlated more strongly with the winter than with the summer precipitation isotope signal due to special features of the site, such as its topography, which resulted in the soil water at the bottom of the valley being efficiently replenished with snow melt from the surrounding steep slopes. Another situation that may influence the cellulose $\delta^{18}O$ could be if the snow-melt water after soil thawing cannot drain into the soil because the ground is still frozen.

Clearly local temperatures and precipitation both influence tree-ring growth and cellulose isotopic composition (which is linked to evapotranspiration and photosynthesis), however at our study site the impact of winter precipitation isotope signal on cellulose $\delta^{18}O$ in larch is greater. This finding can potentially be used to reconstruct past $\delta^{18}O$ of winter precipitation in the European Alps at similar sites on the floor of neo-deglaciated valleys where slope streams are mainly fed by snow melt. More generally, sites with gentle slopes at high altitudes but below the treeline belt, where conditions are too extreme, may also be appropriate locations for reconstructing winter precipitation $\delta^{18}O$ using tree-ring cellulose from European larch.

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