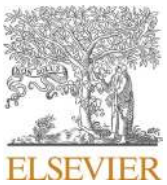
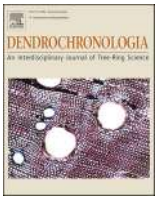
Dendrochronologia 91 (2025) 126322



Contents lists available at ScienceDirect

Dendrochronologia

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Elevation-dependent breakpoint in climate forcing of tree growth in the Turtmann River Basin, Switzerland

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ARTICLE INFO

Keywords:
Tree rings
Elevational breakpoint
Turtmann River Basin
Swiss Alps

ABSTRACT

Tree rings are valuable proxies for reconstructing changes in climate at annual and intra-annual resolutions. In Alpine regions, changes in climate may well lead to switches between tree-growth being temperature-limited and precipitation-limited. Distinguishing between these is important as they may express themselves differently in tree rings. However, such switches cannot be separated from more local environmental influences such as elevation and aspect. In this study, we seek to understand how tree growth evolves as a function of elevation in the context of climate change. For the growth of European larch (*Larix decidua* Mill) in the Turtmann River Basin, a glacier-fed high-elevation river basin in the Swiss Alps, located in southwestern Switzerland, we find that the average temperature increase leads to a switch from temperature-limitation to precipitation-limitation as a function of elevation. The growth of *Larix decidua* Mill in this river basin is influenced by previous year's September-October-November (SON) temperature and current year's January-February-March (JFM) precipitation in the higher- and lower-elevations across an elevational gradient respectively. Based on the analysis from four sites, assuming a linear response, our study suggests that there is a transition zone (i.e., an elevational breakpoint) between 1800 and 900 m AMSL where the signal changes from precipitation-limited to temperature-limited. We also conclude that this elevation breakpoint appears to be rising with time due to increasingly warmer annual average temperatures in this Alpine setting, where this warming is noted to be more than twice compared to the global average temperature change.

1. Introduction

In the Swiss Alps, the average annual temperature has risen by 1.35 °C during the 20th century, which is almost twice as fast as the global average (Rebetez and Reinhard, 2008). This temperature increase has had impacts on precipitation patterns, snow cover, glacier thinning and a substantial glacier retreat of about 57 % since the Little Ice Age, most notable over the last two decades (Hugonnet et al., 2021; Le Roy et al., 2024). The rapid increase in temperature has also led to Alpine ecosystems becoming increasingly susceptible and to these ecosystems rapidly changing across climate gradients and elevation ranges (Pan et al., 2011). Changes in the growth of a number of tree species (conifer species in particular) and treeline elevation have been related to a set of environmental factors (Cuapio-Hernández et al., 2023). These include climatic factors such as air temperature, humidity and solar radiation (Domínguez-Delmás et al., 2013), as well as non-climatic factors such as nutrient availability, soil moisture and landscape fragmentation (Cudlín et al., 2017). Increasing temperature trends are leading to an upward treeline shift in the Alps (Cudlín et al., 2017; Körner, 2012; Paulsen and Körner, 2014). Studies show that treeline elevation varies for different species. For instance, in the Central and Eastern Alps, the treeline ranges between 1000 m and 1900 m above mean sea level (AMSL) for *Picea abies* (L.) H. Karst and 1700 m and 2200 m AMSL for *Larix decidua* Mill (Cudlín et al., 2017). In the Italian Alps, Leonelli et al. (2011) reported an upward shift of the treeline of 115 m between the period 1901–2000 and a further 10 m between 2000 and 2008. In the Swiss Alps, the *Larix decidua* Mill treeline shifted upwards by 167 m between 1972 and 2012, with a shift that was greater on south-facing slopes compared to north-facing slopes (Frei et al., 2023). Rising temperatures in mountains not only force the treeline to shift upwards but the total vegetation cover across the elevation ranges. Gehrig-Fasel et al. (2007) reported that the forest cover in the Swiss Alps increased significantly, a 10 % increase of new forest areas between 1650 m and 2450 m AMSL during the period 1985–1997. Such upward shift in Alpine treelines and increasing forest

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https://doi.org/10.1016/j.dendro.2025.126322
Received 26 February 2024; Received in revised form 1 January 2025; Accepted 24 January 2025
Available online 7 March 2025
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areas may be a clear response to climate change, although it may also be a consequence of changing land use management policies. However, it is important to note the change in the tree-growth limiting climate factors (e.g., temperature limitation) with an increase in growth at higher elevations being possible at increasing average annual temperatures, may also lead to net decrease in precipitation and hence a switch from temperature-limitation to precipitation-limitation. Few studies are available that have investigated elevation-dependent changes and identified the net change in drivers of growth rate in Alpine regions. In the Lötschental Valley in the Central Swiss Alps, King et al. (2013) found that the growth rate of *Larix decidua* Mill and *Picea abies* (L.) H. Karst species became lower towards higher elevation between 1300 m and about 2300 m AMSL and identified a transition from negative to positive correlations between the growing season temperature and ring-width indices (RWI). In the French Alps, Saulnier et al. (2019) observed a significant positive correlation between the RWI of *Larix decidua* Mill and winter precipitation at lower elevations across the range of 1050 m to 2300 m AMSL. Whether such ranges are by themselves changing as a response to climate change also needs to be considered.

This study attempts to quantify climatic influences on tree growth at different sites across the elevational range of 900 m to 2100 m AMSL in the Swiss Alps with the aim of (1) identifying an elevational breakpoint where the signal changes from temperature-limitation to precipitation-limitation; and (2) establishing whether climate change is causing this breakpoint to change in elevation through time.

2. Data and methods

2.1. Site selection

This study focusses on the Turtmann River Basin (110 km^2), located in southwestern Switzerland, between 7°42'E and 46°13'N (Fig. 1). The elevation of this basin ranges from just below 600 m to 4000 m AMSL, with a downward elevation gradient from south to north. The Turtmann Glacier (German: Turtmanngletscher) is situated at the top of the basin (above 2500 m) with an area of 5 km^2 based on the Swiss topo digital elevation model of 2013. The 18 km long Turtmann River originates from the Turtmann Glacier, flows from south to north and joins the Rhone River as a left bank tributary. A hydroelectric power dam at an elevation of 2200 m AMSL, 1.5 km downstream from the glacier, has been in operation since 1958 and transfers most of the glacier meltwater to a neighbouring basin. The Turtmann basin has a distinctive tree species distribution along the Turtmann River from upstream to downstream. The basin is mainly dominated by forest and Alpine pasture (Lane et al., 2022) and the treeline currently extends to 2200 m AMSL. The forest is dominated by *Larix decidua* Mill at higher elevations and by *Picea abies* (L.) H. Karst at lower elevations.

2.2. Tree ring data collection and pre-processing

For this study, cores from living *Larix decidua* Mill trees were collected from three different sites across the elevational range (at 2100 m, 2000 m, and 1800 m AMSL) in October 2021. The sites represent stands with a diverse age structure and without any visible recent human intervention, including evidence of grazing and extreme events, such as rockfalls or floods. The dataset (data code: SWIT255) for a fourth site at 900 m AMSL (Büntgen et al., 2010, 2006) were extracted from the International Tree-Ring Data Bank (ITRDB) located at the basin outlet. The primary reason for using this data is to compare the climatic influence on tree-growth between upstream higher-elevation sites (Site 1, 2 and 3) and a much lower-elevation site (Site 4).

Two increment cores from each healthy tree were extracted at breast height (DBH ~1.5 m above the ground). We took care in coring to avoid eccentricity and compression wood due to slope inclination or prevailing wind direction and other possible external disturbances, including damage due to rockfalls, landslides, and competition from the neighbouring trees. Moreover, in the Alpine environments, several earlier studies have reported the negative influence of the outbreaks of the larch

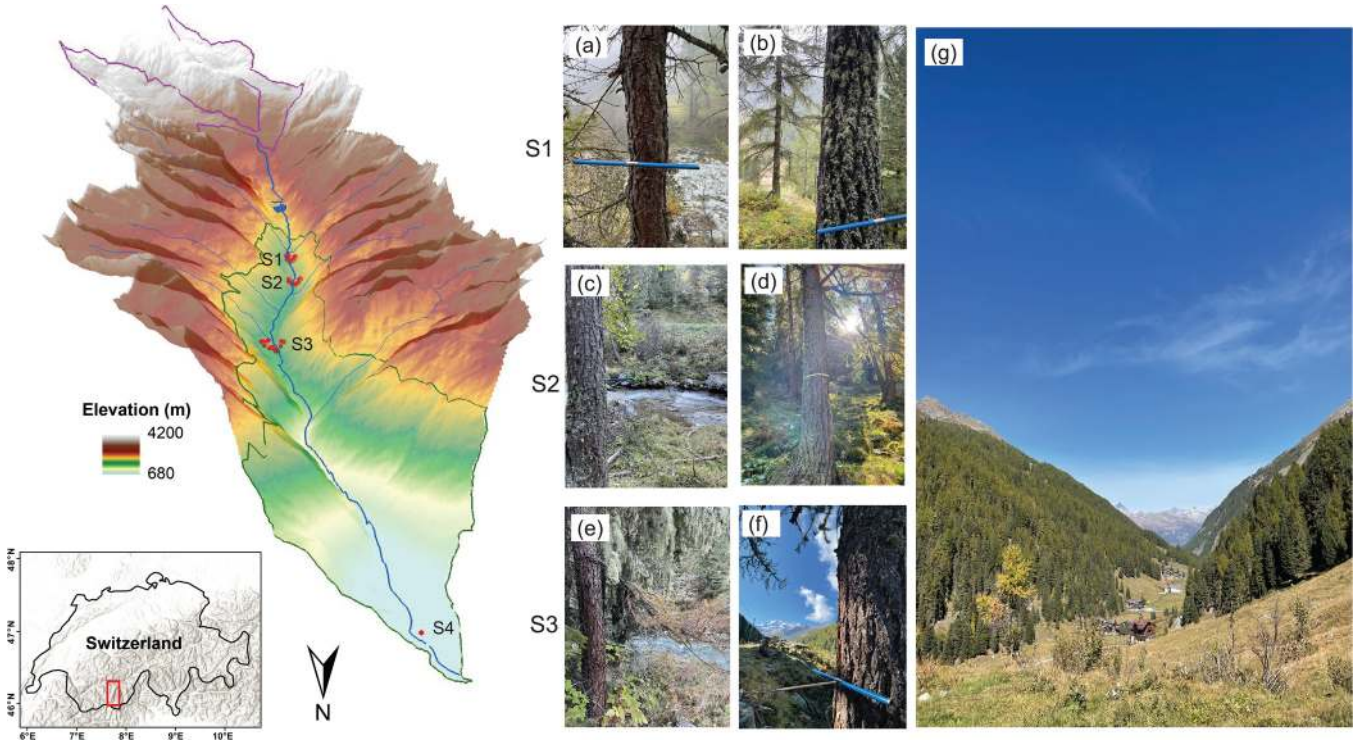


Fig. 1. Study basin and tree-ring sites S1-S4 are shown on the topographic map of Turtmann River Basin (left). Boundaries of the hanging Turtmann Glacier and forest treeline are demarcated on the map by pink and green lines respectively. (a-f) Images from tree-ring sites (S1, S2, S3) collected near the treeline and along the Turtmann River. (g) Image of lower-elevation site (S4) location of Büntgen et al. (2006) chronology downloaded from the ITRDB.

budmoth (i.e., *lepidoptera Zeiraphera dinniana* gn.) which can significantly impact the tree-ring chronologies developed using *Larch decidua* Mill (Baltensweiler et al., 2008; Bjornstad et al., 2002; Büntgen et al., 2020, 2009, 2006; Buras et al., 2016). The larch budmoth has a cyclic period of 8–9 years which introduces defoliation in larch trees due to their larvae and that may create outliers in the ring-width chronologies. Therefore, to avoid any impacts on the chronologies in this study, we have ignored collecting cores from trees with exposed defoliation and further removed cores which had extremely narrow rings. This allowed us to collect 28 cores from each site and in total 84 cores from 42 trees in three different sites (Table S1).

2.3. Instrumental climate data

Meteorological data for the Turtmann River Basin is not available for any one station. As a result, gridded temperature and precipitation data were obtained from MeteoSwiss® (MeteoSwiss, 2010) and downscaled to individual study sites. The mean monthly temperature (TabsM) and total monthly precipitation (RhiresM) datasets are interpolated data, based on a total of 80 stations for temperature and more than 420 stations for precipitation across Switzerland. These datasets have a spatial resolution of 1 km (in the Swiss coordinate system CH1903 +) and cover the period from 1961 to present. Fig. 2 shows the long-term trend in

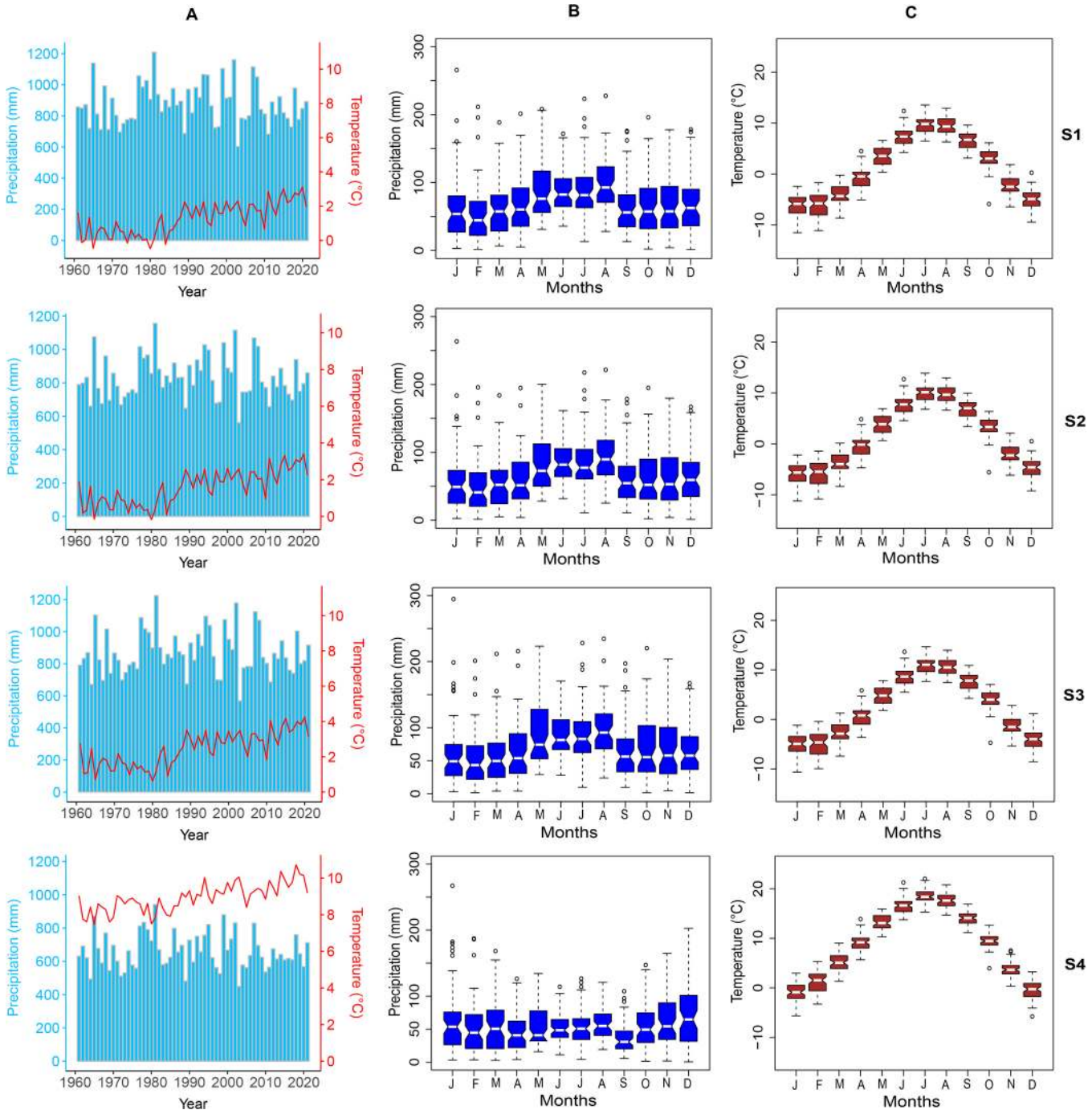


Fig. 2. Time-series plots and climograph summarizing climate at the four tree-ring sites. Sites ordered by decreasing elevation from top (S1) to bottom (S4). (Column A, left) Time plots of annual precipitation and mean annual temperature. (Column B, middle) Boxplots summarizing monthly distribution of precipitation. (Column C, right) Analogous boxplots for temperature. Period of analysis 1961–2021.

total annual precipitation and mean annual temperature, mean monthly precipitation, and temperature for the four sites. The mean annual precipitation during the observation period (1961–2021) is 876 mm (S1), 832 mm (S2), 870 mm (S3), and 660 mm (S4). The corresponding mean annual temperature is 1.2 °C (S1), 1.6 °C (S2), 2.4 °C (S3), and 8.9 °C (S4). Lapse rate between the sites is calculated as 0.4 °C between S1 and S2, 0.8 °C between S2 and S3, 6.5 °C between S3 and S4, with the overall lapse rate between the study sites of 7.7 °C, i.e., an approximate change of 0.6 °C per 100 m in the Turtmann River Basin. This shows a climatic gradient from higher to lower elevation with a mean annual precipitation difference of 216 mm and a mean annual temperature difference of 7.7 °C between site 1 (2100 m AMSL) and site 4 (900 m AMSL). Precipitation data recorded for the period 1961–2021 shows that the Turtmann Basin receives most of its annual precipitation (~42 %) between May and August, which also covers most of the growing season (May-September) of *Larix decidua* Mill at higher-elevation sites across the European Alps (Moser et al., 2009). During this period the average temperature (10.2 °C) is about 6.6 °C higher than the annual average (3.6 °C).

2.4. Tree-ring chronology development

Cores were prepared using standard dendrochronological methods (e.g., sanding/ slicing, cross-dating, ring-width measurement, standardizing, and chronology building) described in the literature (Cook and Kairiukstis, 1990; Fritts, 1976; Schweingruber, 1989; Shroder, 1976; Stokes and Smiley, 1996). The samples were sanded using 400-grit sandpaper and sliced using a core microtome (Gärtner and Nievergelt, 2010) to allow eventual extraction of cellulose for isotopic measurements (not reported here). Cores were then scanned at the WSL, Switzerland, to prepare high-resolution digital images at 5000 dpi. Ring widths were measured from digital images of the cores to a precision of 0.001 mm using the CooRecorder and CDendro software systems (Larsson, 2013). Annual growth increments of each core from individual samples were crossdated against each other visually from common patterns of wide and narrow rings, and statistically by correlation

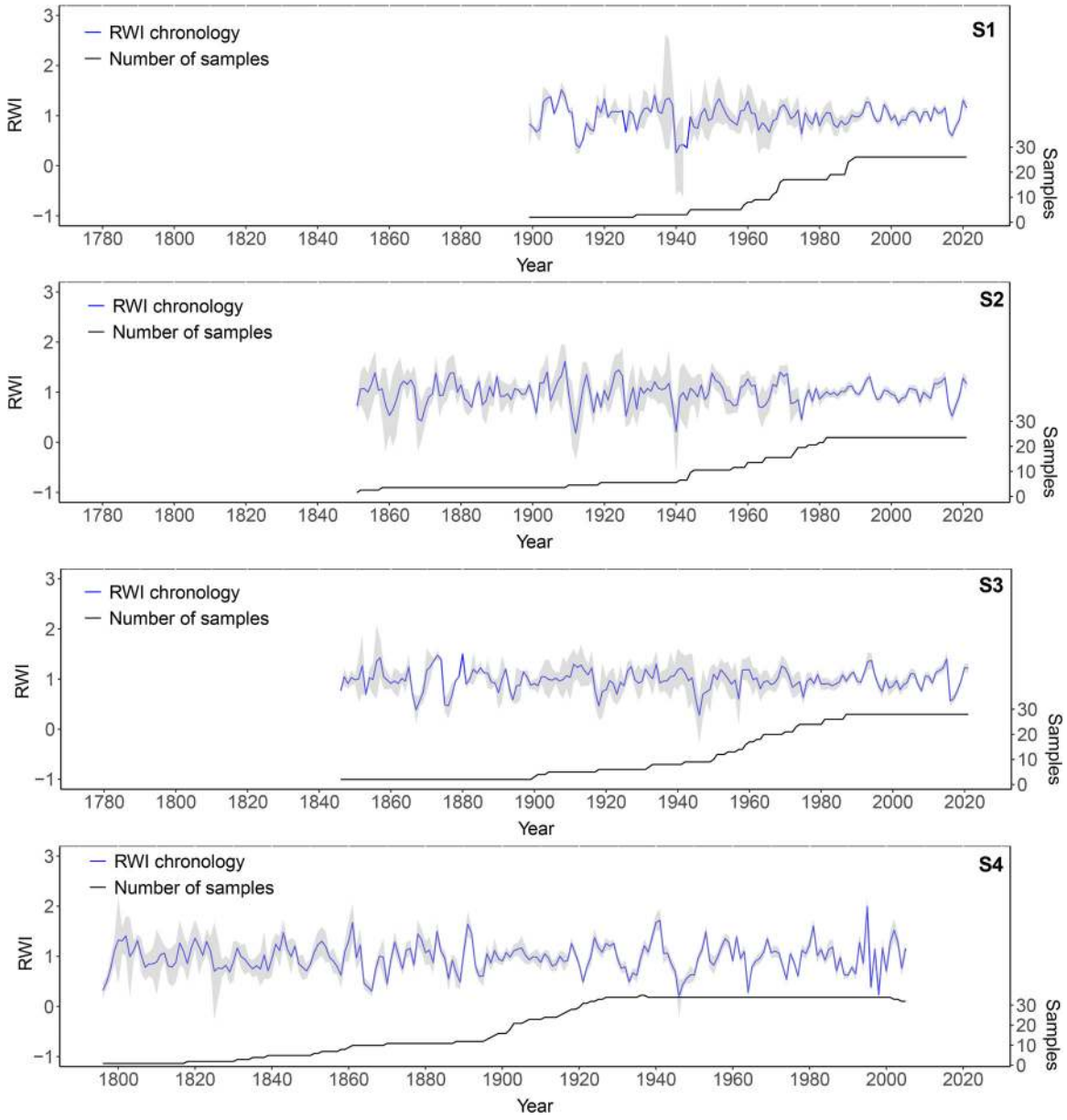


Fig. 3. Ring-width indices (RWI) chronologies of all four sites with uncertainty in the background (grey bar) calculated using bootstrap method and number of samples.

analysis using COFECHA (Holmes, 1983). The satisfactory crossdating (i.e., error-free) allowed us to develop annually resolved ring-width time-series of samples from different locations (e.g., at the proximity and distal to the Turtmann River). We then performed a student's *t*-test to examine whether the growth differences between individual trees at different sites are statistically significant or not. student's *t*-test confirmed that the differences in growth rate of individual cores are statistically significant between sites (i.e., inter-site) but not within the sites (i.e., intra-site). Therefore, we grouped all the cores of individual sites to build four site-specific tree-ring chronologies. In the next step, all the site-specific raw ring-growth time-series were standardized in ARSTAN (Cook, 1985) using a 30-year moving spline detrending technique and the signal-free option (Melvin and Briffa 2008) to remove non-climatic, age-related growth trends (i.e., juvenile effects; Fritts, 1976). This is one of the most frequent fixed spline methods used for detrending tree-ring data and is considered as a high-pass filter preset to preserve short-term high-frequency climate signals in the tree-ring chronology (Klesse, 2021). Two types of ring-width index (RWI) chronologies, the standard and residual chronologies were created. The standard chronology retains more of the medium-frequency variability, while the residual chronology emphasizes high-frequency variability (Cook, 1985). Standard chronologies of all the sites were used for determination of growth-climate responses. The minimum sample size of 5 cores were used in this study to truncate all four site chronologies and plotted with their uncertainty in Fig. 3. The bootstrap confidence limits of 95 % were used to estimate uncertainty in the common signal represented in each site chronology (Efron and Tibshirani, 1994).

We further calculated a suite of diagnostic statistics including the expressed population signal (EPS; Wigley et al., 1984), and total rbar (Briffa, 1999) to evaluate the quality of the four site chronologies located at elevations of 900–2100 m AMSL (Table 1). Total rbar and EPS values in Table 1 apply to the sample size reached in the year 1961, i.e., at the start of the interval used for climate correlations (1961–2020). Standardization and computation of statistics were all done in the R-environment using the 'dplR' package (Bunn, 2010, 2008).

2.5. Growth-climate response function analysis

To determine which climate parameters have significant relationships to the *Larix decidua* Mill growth at all four sites in the Turtmann River Basin, firstly, we calculated the correlation between the raw tree-ring-growth rates and mean annual temperature and total annual precipitation using the Pearson correlation. This allowed us to understand how the tree-ring growths respond to the annual climate (e.g., temperature and precipitation) along the elevational gradient from higher-elevation to lower-elevation sites. The growth-climate relationship was further investigated by considering site-specific monthly and aggregated seasonal climate data to correlate with the RWI chronologies. To do so, we calculated full and partial correlation coefficients of 1-month, 3-month, 6-month and 12-month groupings starting in the September of the previous year to September of the current year using the seasonal correlation program, *seascorr* in Matlab (Meko et al., 2011). Monte Carlo simulation of the RWI chronologies were calculated to establish the confidence intervals for the correlations and partial correlations (Meko et al., 2011) and the significance was estimated using the exact simulation (Percival and Constantine, 2006).

In this study, the standard method was adopted as widely used in the literature to perform the growth-climate correlation analysis between the RWI site chronologies and raw climate data (e.g., temperature and precipitation). However, recent studies have shown that using detrended climate data instead of raw climate data can significantly improve the growth-climate relationship (Ols et al., 2023). An attempt has been made in this study to analyse the monthly and seasonal growth-climate relationships between RWI chronologies and detrended climate data for all four sites using seascorr. However, the results report rather weak and less significant correlations. Therefore, the site-specific raw climate data and RWI chronologies have been used in this study for establishing growth-climate relationships. Once the month(s) or season(s) of optimum period when both temperature and precipitation show maximum significant correlations with RWI was derived using seascorr, stationarity over a longer time-period in the past was analysed using the Pearson's moving window correlation. This was done for the period of 1961–2021 for higher-elevation sites (S1, S2 and S3), and of 1961–2005 for the lower-elevation site (S4). We performed the Pearson's moving window correlation with the minimum and maximum window lengths of 5- and 60-years respectively, based on the available literature (Vuaridel et al., 2019). The sign of the correlation depends on the window size and year, and the correlation values are indicated by the color bars. The results are shown in Fig. 7, of which the top two plots are for temperature (T) and bottom two plots for precipitation (P). Furthermore, the slope of linear regression between RWI and SON temperature, JFM precipitation were calculated to find the transect of switching climatic influence from temperature-limited growth to precipitation-limited growth along the elevational gradient. Positive and negative slopes indicate significant positive and negative correlations between RWI and climate variables respectively (Fig. 8). The slope calculation from the linear relationships between RWI and climate data used in this study follows the similar method earlier used by Vitasse et al. (2019) to investigate changing climate response for the growth of different species across the elevational gradient in the Swiss Alps.

3. Results

3.1. Tree ring growth assessments

The chronologies for the three higher elevation sites (1800–2100 m AMSL) extend back from 2021 to 1899 (S1), to 1851 (S2) and to 1846 (S3), and for the lower elevation site from 1794 to 2005 (S4). These data are available in the Table S2. To assess the climatic responses of annual growth of the trees, we consider the period 1961–2021, which corresponds to the period of available monthly climate data. Fig. 4 shows the tree growth rates through time for all four sites. The average annual growth of 2.0 mm (S1), 1.9 mm (S2), 1.8 mm (S3), and 1.0 mm (S4) varies year-to-year and increases with elevation.

At individual sites, a gradual multi-year increase or decrease in growth, followed by a reversal of the trend is observed (Fig. 4). Marker years, or remarkable growth increase or decrease from the previous years are consistent across the sites, is evident at the higher-elevation sites. For instance, narrow rings (low growth) were recorded in 1975, 1995, 1996, 1997, 2016, 2017, 2018 and 2019 (grey shades). Wider rings (higher growth) were recorded in 1992, 1993, 1994 and 1998 (yellow shades). These patterns contrast with patterns observed at the lower-elevation site (S4) where, 1964, 1973, 1974, 1977, 1989, 1990, 1991, 1992, 1996, 1997, 1998 and 1999 are marker years for low ring

Table 1
Elevations of study sites and statistics for *Larix decidua* chronologies.

Sites	Elevation (m)	Number of trees	Number of cores	Age range/length in years	Rbar (1961–2021)	EPS (1961–2021)	SNR (1961–2021)
S1	2100	13	26	1899–2021 (123)	0.33	0.89	10.32
S2	2000	12	24	1851–2021 (171)	0.43	0.94	15.23
S3	1800	14	28	1846–2021 (176)	0.31	0.89	12.09
S4	900	20	36	1794–2005 (212)	0.57	0.98	45.64

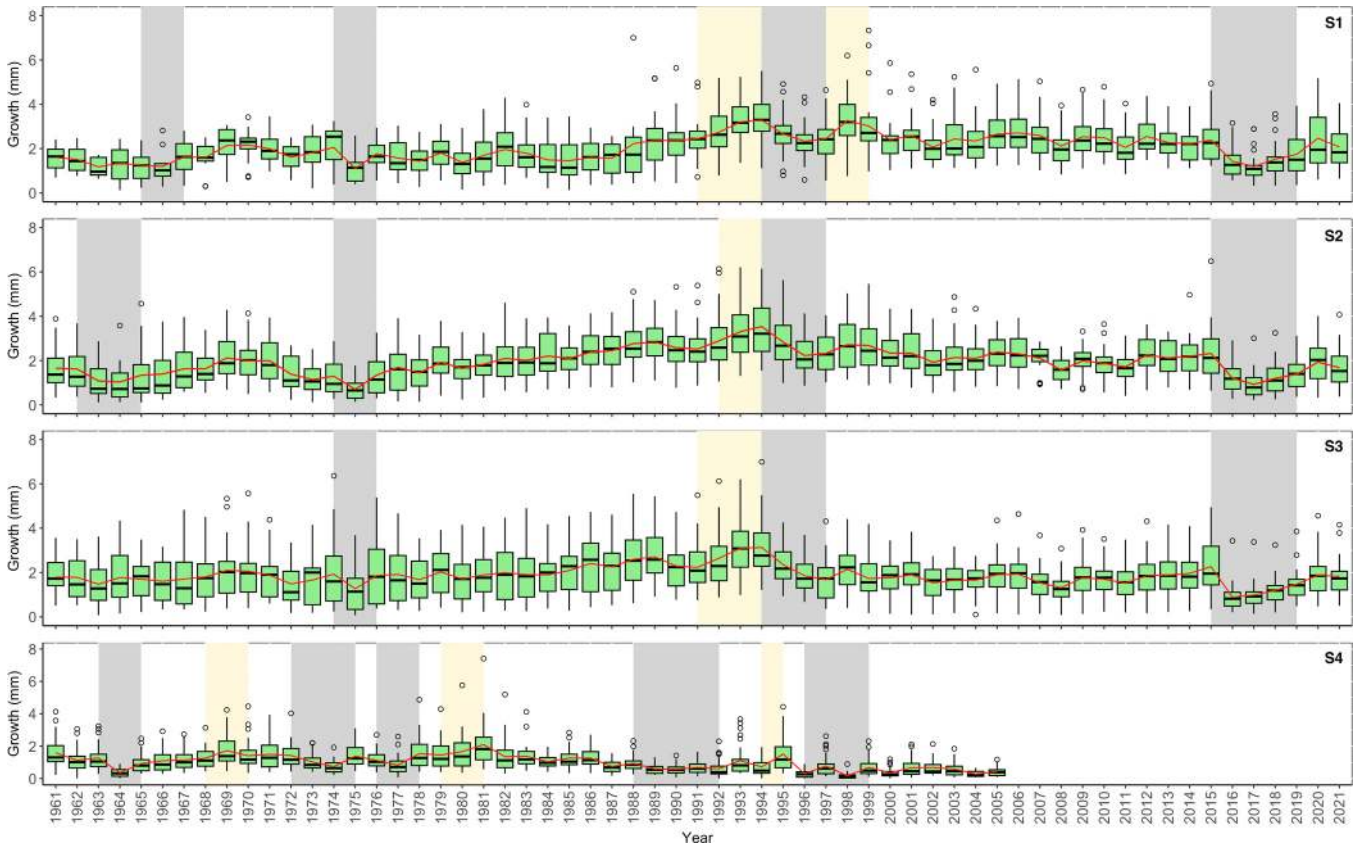


Fig. 4. Annual growth rates at the four tree-ring sites S1, S2, S3 and S4. Boxplot for each year shows the mean (red line), interquartile range (solid bars), and range (whiskers) computed from ring widths at the site. The background grey and yellow shades highlight periods of low and high growth respectively.

growth, and 1969, 1980, 1981, and 1995 for high ring growth. Differences in growth between sites likely reflect the effects of site-specific microclimates (e.g., temperature, precipitation) of the previous and current years. For instance, the growth decrease in 1975 in all three higher-elevation sites may reflect the sharp decrease in temperature in 1974, i.e., 0.6 °C lower than the previous year's average temperature. The year 1974 has been recorded as one of the coldest years in the MeteoSwiss® climate archive. A similar pattern was also observed more recently with relatively low temperatures in 2016 and 2017 associated with lower growth in those years. Besides direct climatic influences, other factors related to geomorphology such as slope-failure, rockfalls, debris-flow and other mass-movement processes can also impact tree growth in this basin (Messenzehl et al., 2017).

3.2. Growth-climate relationships

3.2.1. Tree-growth response to annual climate

The scatter plots in Fig. 5 show that there is a positive relationship between annual ring-growth and mean annual temperature in the high-elevation sites (S1, S2 and S3). This relationship is significant ($p < 0.05$) at site 1 and site 2 but weaker at site 2 and becomes non-significant at site 3 ($p > 0.05$). The relationship between tree growth and mean

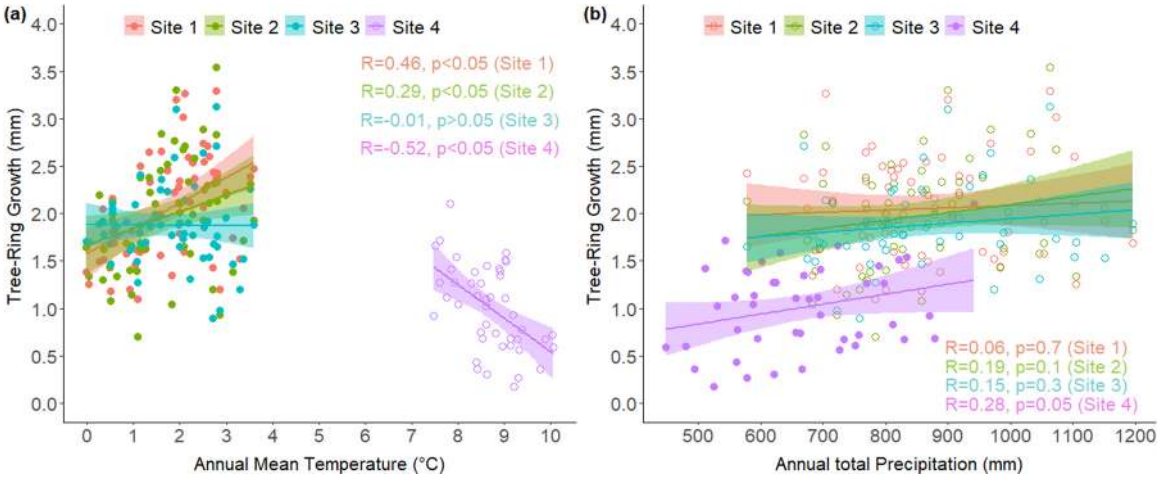


Fig. 5. Scatter plots of tree-ring growth rate against the annual mean temperature (a) and total precipitation (b) at all four sites (S1, S2, S3 and S4). Period of analysis 1961–2021.

annual temperature is negative ($p < 0.05$) at the lower-elevation site 4. This suggests that temperature plays a key role in influencing the growth of *Larix decidua* trees at higher elevations in the Turtmann Basin and indicates that the direction of temperature influence on growth is elevation dependent. Unlike temperature, precipitation shows no reversal in direction of influence on growth from high to low elevation (Fig. 5). The precipitation correlation is insignificant at higher elevations, but significant and positive at lower-elevation site 4. Moreover, the Pearson correlation analysis confirmed no significant correlation ($p > 0.05$) between the annual average temperature and total precipitation for any of the four sites over the study period. Therefore, the concordance between temperature and precipitation at the study sites is low.

3.2.2. Tree-growth response to monthly and seasonal climate

The results of monthly and seasonal correlations in Fig. 7 show that the optimum correlation period is three months and varies for temperature and precipitation from higher to lower elevation sites. For instance, warm previous year's autumn temperature (September-October-November, SON) favors the growth of *Larix decidua* as the correlation of SON temperature with the RWI chronologies is positive and significant at site 1 ($r = 0.32$, $p < 0.01$), site 2 ($r = 0.44$, $p < 0.01$) and site 3 ($r = 0.39$, $p < 0.01$). The growth-temperature correlation patterns, both for the seasonal and individual months are similar in all three high-elevation sites. At site 4, no individual month or season shows any significant correlation with temperature. In contrast, the current year's winter and early spring precipitation (Jan-Feb-March, JFM) is positively associated with ring width indices (RWI) chronologies and statistically significant ($r = 0.44$, $p < 0.01$) at site 4. However, an exception to the usual growth-precipitation correlation pattern can also be noticed in Fig. 6. It shows that the precipitation of current year April is positively correlated with the ring-width chronology at site 2 ($r = 0.21$, $p < 0.05$) and at site 3 ($r = 0.30$, $p < 0.05$), but the correlation is weak.

3.2.3. Long-term trends in growth-climate relationship

Based on the monthly and seasonal response function analysis as shown in Fig. 6, the windowed Pearson correlation analysis was performed between site chronologies (RWI) and climate data (e.g., SON temperature and JFM precipitation). The results in Fig. 7 suggest that the positive response of previous year's SON temperature is significantly higher over the temporal periods (1961–2021) at the higher elevation upstream sites. Whereas the current year's JFM precipitation is the main driver for limiting growth of trees at the lower elevation site throughout the analysis period (1961–2005).

Fig. 7 reveals three major periods of changing temperature influence on tree growth in the higher elevation upstream sites, such as 1961–1980, 1981–2001, and 2002–2021. For instance, in the first period (two decades) of the analysis period from 1961 to 1980, a significantly higher positive correlation between RWI chronologies and SON temperature was observed, and this is followed by the second period when this relationship turned negative for the next two decades from 1981 to 2001. Most recently, a significant positive correlation has been noticed again in the third period since 2002. This common pattern of changing response of SON temperature to tree growth is relatively constant over the longer periods. On the other hand, at the lower-elevation downstream Site 4, the relationship between RWI and SON temperature shows negative correlation with the exception during 1990 and 2000, when the relationship turns into positive, but the correlation is weak.

Moreover, in contrast to the decadal variations in SON temperature influence, JFM precipitation has more short-term influence on tree growth in the upstream higher elevation sites, and the growth-precipitation relationship is not as straightforward as it is for

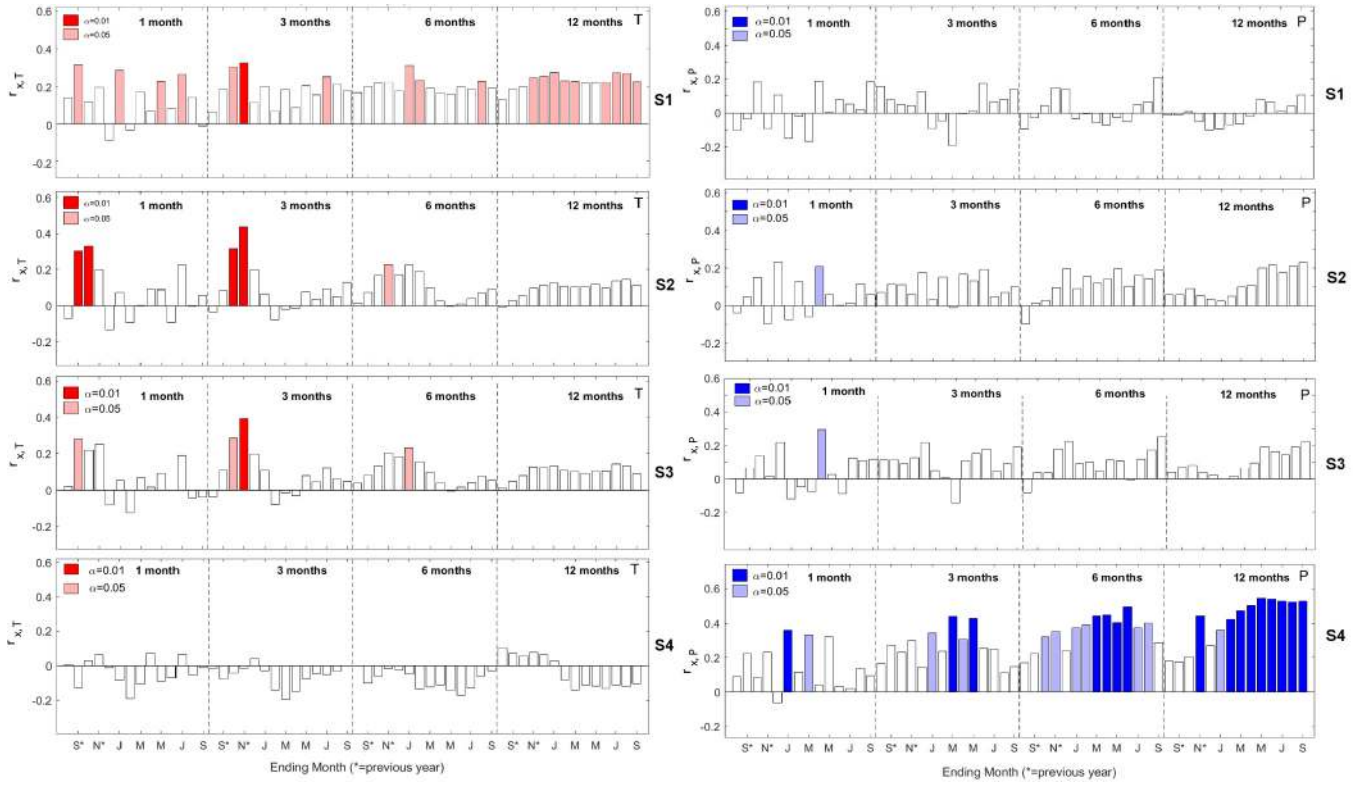


Fig. 6. Bar-chart summary of correlation of site chronologies with monthly and seasonally aggregated climate data. For the four sites (top to bottom), plots show correlation with temperature (T; red) and precipitation (P; blue) for individual months (1 month) and for the *n*-month average or sum over $n = 3$, 6 and 12 months ending in month marked on x-axis. Significance levels indicated by light or dark shading and estimated by exact simulation at $p < 0.01$ and $p < 0.05$ (Percival and Constantine, 2006). Plots and statistics output by program Seascorr (Meko et al., 2011). Period of analysis 1961–2021.

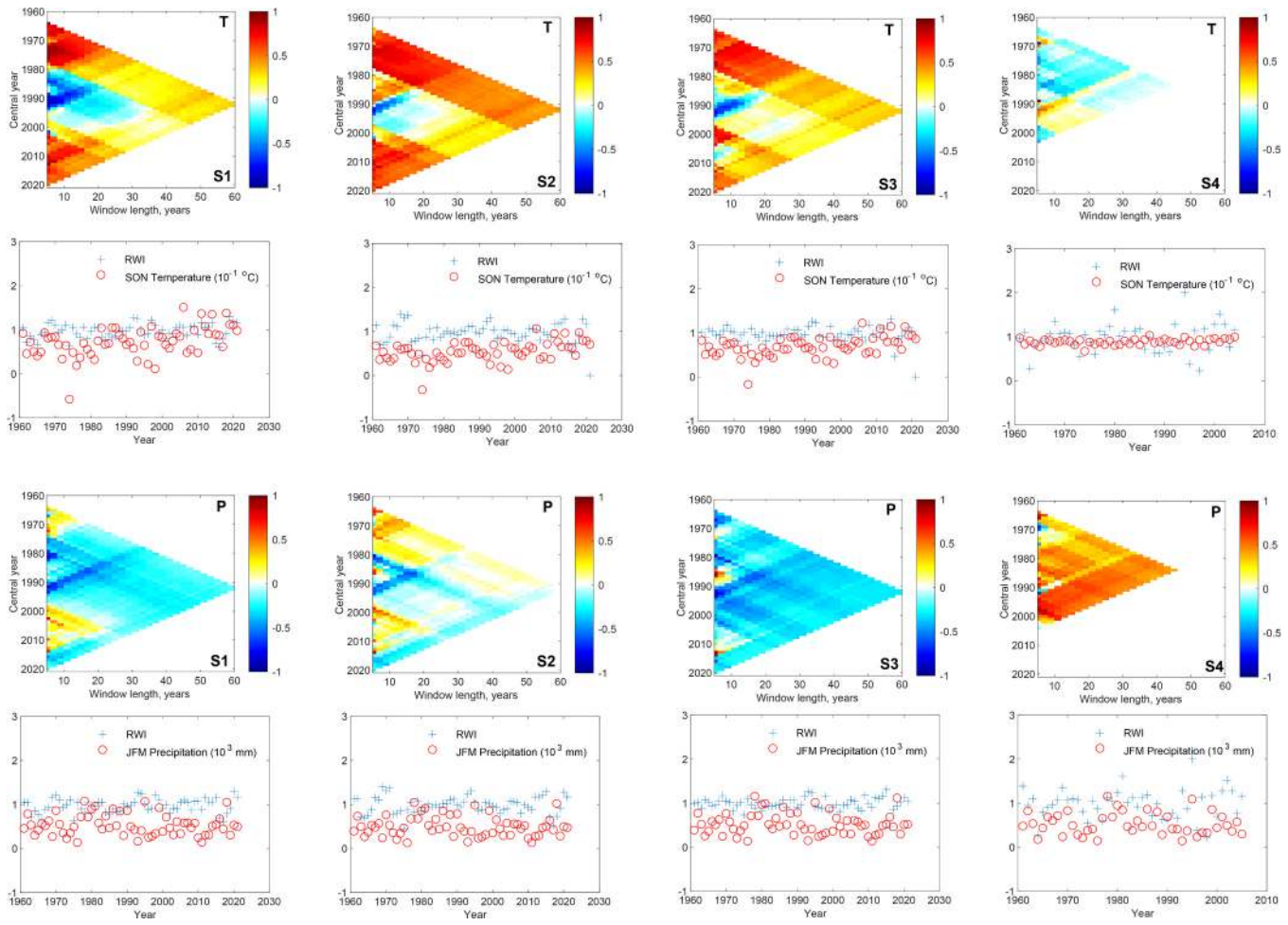


Fig. 7. Time-dependent relationships of chronologies to climate summarized by windowed correlations and time plots. RWI chronologies are ordered from high to low elevation from left to right. The top two plots are for SON temperature (T) and bottom two plots for JFM precipitation (P). Color maps show windowed correlations (centered) for window sizes 5–60 years (S1, S2, S3) and sizes 5–50 years (S4). Below the color map is the corresponding time series of SON temperature or JFM precipitation. Period of analysis 1961–2021.

temperature across the elevational gradient. For instance, Fig. 7 shows that at Site 1, JFM precipitation often correlates mostly negatively with the RWI chronologies at all three higher-elevation sites, except few individual years during 1970s, 2000s, and 2010s with relatively shorter window lengths that show positive correlations. Compared to the upstream higher elevation sites, the lower-elevation Site 4 at the basin outlet shows significantly strong positive correlation between RWI and JFM precipitation throughout the analysis period (1961–2005). Based on the climate response to tree growth over a longer period, such as a 60-years of window length for SON temperature, and a 45-years of window length for JFM precipitation, it is expected that their relationships might be more significant in recent decades. However, this cannot be confirmed in this study due to the lack of recent tree ring data. Moreover, the significant positive correlation between RWI and SON temperature at higher elevation sites and between the RWI and JFM precipitation at lower-elevation site over the longer period demarcates a hydro-climatic partition for limiting tree growth across the elevational gradient in the Turtmann River Basin.

3.3. Elevation-dependent breakpoint in the switch between temperature and precipitation limitation of growth

The growth of *Larix decidua* Mill in the high-elevation sites within the range 1800–2100 m AMSL shows a strong dependence on previous year's SON temperature and current year's JFM precipitation. Higher elevation upstream sites (S1, S2 and S3) within 2100–1800 m AMSL have significant positive relationships ($p < 0.05$) between RWI chronologies and SON temperature, and their relationships show similar slopes (Fig. 8). Moreover, a slightly negative slope of the linear regression between RWI and SON temperature at Site 4 indicates that the temperature becomes a less significant factor for limiting growth of *Larix decidua* Mill in the low-lying areas at 900 m AMSL. In contrast, a significant positive relationship between RWI and JFM precipitation as shown by the slope of their linear regression at Site 4 indicates a strong precipitation dependency for tree growth. The area between Site 3 and Site 4 (i.e., between 1800 m and 900 m AMSL) acts as the critical transition zone where the climatic response switches from positive to negative and vice versa for both temperature and precipitation.

4. Discussion

Four century-long RWI chronologies (Fig. 3) developed from the *Larix decidua* Mill for four sites across an Alpine elevational gradient show distinctive growth patterns including low- and high-growth periods in consecutive years (Fig. 4). Methodologically, there were several samples with a few missing rings, resin-ducts, compression wood, extremely narrow rings, cell-damaged rings, and poor wood quality which presented a challenge for cross-dating (Fig. S1). Samples with compression wood can be linked to the occasional mass-movement processes including rockfalls as the headwater catchment is

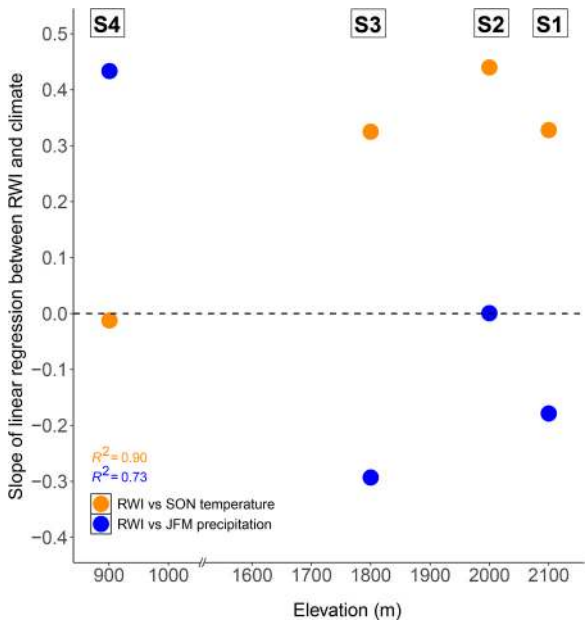


Fig. 8. Elevation dependence of slope of regression line of site chronologies on climate. Dots indicate slopes of linear regressions of ring width indices (RWI) with SON temperature and JFM precipitation between 1961 and 2021 for higher-elevation sites (S1, S2 and S3), and between 1961 and 2005 for the lower-elevation S4.

susceptible to rockfall events. However, these challenges aside, it was possible to develop chronologies for three sites to add to the ITRDB database. The sample depth (i.e., total number of cores) decreases over time in the site-chronologies, leading to higher uncertainty. Therefore, the selection of chronology length was restricted to only 60 years from the recent time (i.e., 1961–2021) which replicates more than ten cores for each site. This allowed us to analyse the growth response to available climate data over this period. The relationships between tree-ring growth and climate data (e.g., annual temperature and precipitation) shows a significant climatic response on tree growth across the elevational gradient based on Pearson's correlations (Fig. 5). However, the correlations between raw tree-ring growth and climate data may have the tendency to hide variability in associations over different timescales and at different growth periods. Windowed Pearson correlations between site chronologies (RWI) and monthly temperature and precipitation suggest the optimum month(s) and seasons for highest climate response (Fig. 6) and allows the time-dependence as well as elevation contrast in tree growth response to climate to be identified at the four sites.

4.1. *Larix decidua* growth responses to temperature at higher elevation sites

Our results show significant correlations between *Larix decidua* Mill growth and seasonal temperature at the three highest-elevation sites. The growth of *Larix decidua* Mill is significantly influenced by previous year's autumn temperature during September-October and November at higher elevation sites in the Turtmann River Basin (Fig. 6). Thus, whilst our study does indeed suggest that temperature is controlling tree growth at higher elevation sites, the previous year's SON temperature is more significant for site 1, 2 and 3 located within 1800 m to 2100 m AMSL compared to current year summer temperature in June-July-August (JJA) as reported in previous studies (Büntgen et al., 2009, 2006). Certain species, notably *Larix decidua* Mill, *Pinus cembra,* and *Pinus sylvestris* at high-elevation sites across the European Alps have a general tendency of a positive growth response to temperature during the previous year, autumn in particular (Frank and Esper, 2005; Leonelli et al., 2017; Nagavciuc et al., 2019; Saulnier et al., 2019).

In terms of the response of SON temperature on RWI chronologies over a longer temporal period (1961–2021), the Pearson moving window correlation analysis suggest that SON temperature has significantly influenced tree growth in three different periods (1961–1980, 1981–2001, and 2002–2021) in all three high-elevation sites (Fig. 7). This common decadal growth-temperature correlation pattern in the higher-elevation sites is most likely due to sufficient water availability in this glacierized river basin through snow and glacier-melt. Whereas the negative correlation during the period 1980–2000 can be linked to the fact that since the 1980s an exponential increase in temperature has been observed across the Alps (Haeberli and Beniston, 1998), including in the Turtmann Basin as shown in the climograph (Fig. 2). The impact of such rapid temperature increase reflects on observations of several meters of upward shift of treeline following recent temperature warming across the Alps (Cudlín et al., 2017; Körner, 2012), including the Aosta valley, Italy (Leonelli et al., 2011), Dischma valley, Switzerland (Frei et al., 2023). This continuous increase of temperature may have led the climate influence to reach an optimum for influencing tree growth, and therefore the later negative correlation suggests that the SON temperature was no longer a significant growth limiting-factor for *Larix decidua* species in the higher-elevation sites. Moreover, the positive response of SON temperature to tree growth in the third climatic period (2002–2021) can be linked to the recent cooling in the Alps including in the Turtmann Basin where several years with below average temperature have been recorded (e.g., 2004, 2005, 2010, 2013, and 2021). Compared to high-elevation upstream sites, no such changes in climatic response to tree growth is visible in the low-elevation downstream site 4. Several previous studies have discussed how warmer summer temperatures may enhance tree growth at high-elevation, cooler sites where the growing seasons are generally short (Büntgen et al., 2006; Miyamoto et al., 2010; Savva et al., 2006).

4.2. *Larix decidua* growth responses to precipitation in lower elevation sites

The relationship between growth and temperature is straightforward, with clear variations in changing response in three distinctive periods as a function of elevation. On the other hand, our analysis shows that annual precipitation has a significant positive correlation ($r = 0.28$, $p < 0.05$) with ring growth rate at the lower elevation site 4 (900 m AMSL) but no significant correlation at the higher elevation sites, above 1800 m AMSL (Fig. 5). In contrast, *Larix decidua* Mill growth at site 4 is strongly influenced by current year's precipitation in January, February and March. The significant positive relationship with JFM precipitation ($r = 0.44$, $p < 0.01$) could be amplified by the vapor pressure deficit, which tends to increase with low precipitation and dry soil (Moser et al., 2009). In the Alps, *Larix decidua* Mill starts growing in April at low elevations (Bugmann et al., 2014; Moser et al., 2009), comparatively early than at higher elevations, where growth starts in June (Büntgen et al., 2006; Frank and Esper, 2005). As a result, the availability of winter and spring precipitation along with soil moisture limits the growth in lower elevation sites. Whereas at the higher elevation sites atmospheric moisture, snow, and glacier-melt provides water during the growing season. Precipitation is thus expected to be a non-significant or less significant climatic factor for tree growth in the higher elevation sites. With climate warming, this favorable impact of snowmelt could decrease as the snow percentage of precipitation decreases and snowmelt runoff is accelerated (Rammig et al., 2010; Vorkauf et al., 2021). Earlier studies have shown that the growth of *Larix decidua* Mill in the Swiss Alps correlates negatively with summer precipitation ($r = -0.40$, $p < 0.01$) between 1900 and 2200 m. AMSL (Büntgen et al., 2006). In contrast, our results show that there are several individual years during 1970s, 1980s and recently in 2000s when positive correlations between RWI and JFM precipitation in high-elevation sites between 1800 and 2100 m. AMSL have been observed (Fig. 7). However, these correlations

are weaker and often less significant. The influence of JFM precipitation (despite its weak correlation) on tree growth at higher elevations, is likely to influence the temperature limitation too, with a tendency towards drier conditions due to the increase of temperature across the Alps in recent decades (Treydte et al., 2023; Vitasse et al., 2019). Increasing temperature leads to drought-like conditions and in such dry atmospheric conditions, plants are under stress due to the photoinhibition (Adams et al., 2013; Demmig-Adams and Adams, 2016). Such dry atmospheric conditions prevailing in the low-lying areas in a mountain catchment may well be a reason for the positive correlation of *Larix decidua* Mill growth with JFM precipitation at the lower-elevation Site 4 in this study. This suggests that particularly at the lower elevation site, warm conditions may limit water availability, most likely affect tree growth negatively in future in the Turtmann River Basin.

Overall, the RWI chronologies of the *Larix decidua* Mill correlate positively with SON temperature at high-elevation sites 1, 2 and 3 (between 1800 m and 2100 m AMSL) and with JFM precipitation in the lower-elevation site 4 (900 m AMSL). The growth-climate relationship across the elevational gradient suggests that due to their locations in the headwater glacierized areas, trees at sites 1, 2 and 3 mostly receive water from different sources such as snow and glacier melt, whereas the trees at the lower elevation site receive water mainly from rain and soil moisture. Thus, the critical transition zone where climatic influence on tree growth switches from temperature-limitation to precipitation-limitation in the Turtmann Basin is most likely in between Site 3 (1800 m AMSL) and Site 4 (900 m AMSL). This is based on the evidence from the seasonal correlations and the slope of linear regression between RWI and SON temperature, JFM precipitation. Critical transition zones across the elevational gradient can vary spatially and in different climatic regimes. Therefore, data from multiple sites across an elevational gradient may help to better identify the transition zone. In this regard, Vitasse et al. (2019) identified ~1300 m as the critical transition zone for tree growth in multiple sites across the Swiss Alps. Below this altitude, *Larix decidua* Mill and *Picea abies* respond negatively to summer temperature. However, under rapid warming, and given the positive correlation between tree growth and temperature and precipitation in the last decades, tree lines have been widely reported to shift upwards across the Alps (Leonelli et al., 2011). The transition zone between precipitation and temperature response logically would also shift in the Turtmann River Basin.

5. Conclusion

This study compares four site-specific *Larix decidua* Mill chronologies with the climate data for the period of 1961–2021. This unveils a multi-decadal growth-climate relationship history of Turtmann River Basin from upstream to downstream. Our analysis reveals growth-climate relationships with decadal variations of changing temperature and precipitation response to tree growth over a long period (1961–2021). We have also highlighted the seasonal climatic influence on tree growth such as previous year's autumn (SON) temperature and current year's winter-spring (JFM) precipitation. The findings also support an elevation effect on tree growth. Based on our analysis from four sites, assuming a linear response it can be stated that between site 3 (at 1800 m AMSL) and site 4 (at 900 m AMSL) there is likely a transition zone (i.e., the elevational breakpoint) where the signal changes from precipitation-limitation to temperature-limitation across the elevational gradient in the Turtmann River Basin. However, to provide clear evidence of elevational breakpoint, more rigorous studies from multiple sites at higher temporal resolutions are recommended. We also conclude that recent changes in climate, expressed as an increase in temperature, cause this breakpoint to shift to higher elevations within the Swiss Alps. Therefore, the findings of this study may help forest managers to better understand the ongoing climate change impact on *Larix decidua* Mill growth in the Turtmann Basin for sustainable forest management. The focus of future studies may be on the understanding of how other hydroclimatic parameters such as snowmelt besides temperature and precipitation can also influence *Larix decidua* Mill growth in high elevation Alpine River basins under the future climate warming.

CRediT authorship contribution statement

Meko David: Writing – review & editing, Supervision. **Lane Stuart:** Writing – review & editing, Supervision, Funding acquisition. **Islam Nazimul:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Vennemann Torsten:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nazimul Islam reports financial support was provided by Federal Commission for Scholarships for Foreign Students (FCS), Swiss Government Excellence Scholarship. Nazimul Islam reports a relationship with Laboratory of Tree-Ring Research, University of Arizona (Haury Fellowship) that includes: funding grants and travel reimbursement. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are thankful to the Federal Commission for Scholarships for Foreign Students (FCS) for the Swiss Government Excellence Scholarship (Grant No: 2020.0271) to conduct this research, and equally thankful to the Swiss Federal Research Institute WSL, Switzerland for access to laboratory equipment to process the samples. We would also like to extend our gratitude to the staff at the Laboratory of Tree-Ring Research (LTRR), University of Arizona, USA, for providing the facilities and technical guidance in measurement of samples, analysis of data, and compilation of results. Lastly, the support from colleagues from the institute (IDYST) in the field for data collection is highly appreciated.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2025.126322.

Data availability

Data will be made available on request.

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