Geogr. Fis. Dinam. Quat.
41 (2018). 35-49, 6 figg., 3 tabb.

DOI 10.4461/ GFDQ.2018.41.3

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DENDROCLIMATIC RELEVANCE OF "*BOSCO ANTICO*", THE MOST ANCIENT LIVING EUROPEAN LARCH WOOD IN THE SOUTHERN RHAETIAN ALPS (ITALY)

ABSTRACT: CERRATO R., SALVATORE M.C., BRUNETTI M., COPPOLA A. & BARONI C., *Dendroclimatic relevance of "Bosco Antico", the most ancient living European larch wood in the southern Rhaetian Alps (Italy).* (IT ISSN 0391-9838, 2018).

The ongoing increase in the global mean temperature at an unprecedented recorded rate is well documented. Nevertheless, knowledge of past climate variations is fundamental for a better understanding of ongoing climate change. This need is crucial in high mountain areas, where the effects of global warming are amplified and induce an accelerated glacial retreat. Thus, the use of climatic proxies such as tree-ring width offers tools to better understand the environmental dynamics in remote, sensitive sites. Here, we present the "*Bosco Antico*" site chronology, a six-century long dataset from the most ancient living stand in the Val di Sole area (southern Rhaetian Alps, Italy), and its relationship with summer mean temperatures. The analyses were performed on earlywood and latewood separately, as well as on tree-ring widths using static and moving correlations. The results showed that tree-rings and earlywood width are linked with June temperatures, whereas latewood width is mainly driven by July temperatures. All the analysed series were greatly influenced by June to July and June to August temperatures. Finally, a mean summer latewood-based temperature reconstruction since 1525 is proposed. It highlighted that during the last six hundred years, the summer temperatures span between -2.3 to +1.9 °C compared to the 1960–90 mean temperature (between 6.2 and 10.4 °C at the stand elevation). The coolest phase is recorded in the 1810s-20s underlining the strongest pulse of the Little Ice Age; other phases of negative anomalies are recorded in the first half of the 17th century, around 1700, and 1900 and during the 1970s. Our results add an important dataset for a specific climatic area, providing new information that will contribute to a better understanding of the climate dynamics for the study site as well as on a larger scale.

KEY WORDS: Tree-rings, Earlywood chronology, Latewood chronology, Dendroclimatic series, Summer temperatures, Val di Sole, Rhaetian Alps.

RIASSUNTO: CERRATO R., SALVATORE M.C., BRUNETTI M., COPPOLA A. & BARONI C., *L'importanza dendroclimatica del "Bosco Antico", il più antico bosco di larice vivente nelle Alpi Retiche Meridionali (Italia).* (IT ISSN 0391-9838, 2018).

L'attuale aumento delle temperature medie globali ad una velocità mai registrata in precedenza è un'evidenza ben documentata. Tuttavia, la conoscenza delle variazioni climatiche del passato è fondamentale per meglio comprendere il cambiamento climatico in atto. Questa necessità è cruciale soprattutto nelle aree montane, dove l'effetto del riscaldamento climatico è amplificato e induce un accelerato ritiro dei ghiacciai. Quindi, l'utilizzo di *proxy* climatici, come ad esempio l'ampiezza degli anelli degli alberi, offre importanti strumenti per definire le dinamiche ambientali in siti remoti sensibili. Nel presente lavoro presentiamo la cronologia di "*Bosco Antico*", un dataset lungo seicento anni ottenuto dal più antico bosco vivente di larice nella Val di Sole (Alpi Retiche Meridionali), e le sue relazioni con le temperature medie estive. Le analisi sono state effettuate misurando le ampiezze del legno primaticcio e di quello tardivo, separatamente, e l'ampiezza annuale utilizzando correlazioni statistiche. I risultati evidenziano che l'ampiezza anulare e l'ampiezza del legno primaticcio sono influenzate dalle temperature di giugno mentre l'ampiezza del legno tardivo è maggiormente influenzata dalle temperature medie di luglio. Tutte le serie analizzate sono risultate essere altamente correlate con le temperature medie di giugno-luglio, giugno-luglio-agosto. Infine, viene proposta una ricostruzione delle temperature medie estive a

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This work was financially supported by the Italian MIUR Project (PRIN 2010-11): "Response of morphoclimatic system dynamics to global changes and related geomorphological hazards" (national and local coordinator: C. Baroni) and by the project of strategic interest NEXTDATA (PNR National Research Programme 2011-2013; project coordinator A. Provenzale CNR-IGG, WP 1.6, leader C. Baroni UNIPI and CNR-IGG). We wish to thank Dr. Fabio Angeli, responsible for the Ufficio Distrettuale Forestale of Malè (Trento), for sampling permission. We thank Carrer M. and an anonymous referee for their comments and discussion. All the authors contributed at the development of this study: CB, MCS and RC carried out the fieldwork activities and RC was the responsible of the laboratory work and analyses. MB supplies the interpolated meteorological data. The text was written by RC and revised by CB, MCS, AC and MB. All the authors contributed in equal manner at the realization and correction of the final version of the paper in all its parts. The project was designed, coordinated and funded by CB. The English text has been edited by American Journal Experts (certificate verification key: C0A5-12B9-E55B-177F-3910).

partire dal 1525 basate sull'ampiezza del legno tardivo. La ricostruzione evidenzia come negli ultimi seicento anni le temperature abbiano subito oscillazioni tra -2.3 e +1.9 °C rispetto alla media del periodo 1960–90 (equivalenti a temperature medie di 6.2 e 10.4 °C alla quota del sito). La fase più fredda è registrata tra gli anni '10 e '20 del 1800 e sottolinea la pulsazione più vigorosa della Piccola Età Glaciale; altre fasi di anomalie negative sono registrate nella prima metà del XVII secolo, intorno al 1700, intorno al 1900 e durante gli anni '70 dello stesso secolo. I nostri risultati aggiungono un importante dataset per una particolare area climatica, fornendo nuove informazioni che contribuiranno ad una migliore comprensione delle dinamiche climatiche sia dell'area di studio sia a una scala più ampia.

Termini Chiave: Anelli di accrescimento, Cronologia *Earlywood*, Cronologia *Latewood*, Serie dendroclimatiche, Temperatura estiva, Val di Sole, Alpi Retiche.

INTRODUCTION

The increase in global temperatures at an unprecedented recorded rate is well documented (IPCC, 2013), and data availability increased during the past decades (Rennie & *alii*, 2014). Instrumental data series of different climatic parameters such as temperature, precipitation and sea level pressure, exist for the past two centuries for the most populated areas (Allan & Ansell, 2006; Smith & *alii,* 2012; Rennie & *alii,* 2014). Nevertheless, to analyse climate change in a long-term context, climate information from the pre-industrial era is needed. Proxy data reflective of environmental parameters are fundamental for retroactively inferring and reconstructing climatic variables. Several proxies such as pollen, speleothems, ice-cores and corals are widely used to obtain long-term paleoclimate information (IPCC, 2013); among these, tree-rings make it possible to obtain annually resolved and precisely dated temperature information from the late Holocene and from disparate environments (Schweingruber, 1988; Wilson & *alii*, 2016; Anchukaitis & *alii*, 2017). In particular, in high-latitude and high-altitude areas, tree-rings are fundamental temperature proxies (Briffa & *alii*, 2002; 2004; Bojinski & *alii*, 2014).

In Europe, one of the areas most dramatically affected by the increasing temperatures is the Greater Alpine Region (GAR; Auer & *alii*, 2007). In this area, the cryosphere plays an important role in landscape and ecosystem dynamics; at the present time, climate change is producing the most dramatically and historically unprecedented glacier decline (Zemp & *alii*, 2015) and inducing changes that affect the glacial foreland in the process (Whelan & Bach, 2017). In the Italian Alps alone, glaciers are shrinking and collapsing (Baroni & *alii*, 2015, 2016, 2017a; Zemp & *alii*, 2015) and have lost 27% of their area in the last fifty years (Salvatore & *alii*, 2015). Thus, a proxy that allows for reliable reconstructions of past temperature variations at these sensitive sites is fundamental to better understanding ongoing climate change and to producing realistic estimates about the future of the cryosphere in the Alps.

Using tree-rings as a temperature proxy, several hemispherical and continental temperature reconstructions have been proposed (Büntgen & *alii*, 2006, 2011; Battipaglia & *alii*, 2010; Trachsel & *alii*, 2012; Leonelli & *alii*, 2016). However, to perform these reconstructions and make them reliable, both regional and local tree-ring chronologies are needed (Esper & *alii*, 2016). Understanding general trends is essential to assessing climate variation on a planetary scale, but local reconstructions can supply information that may be not completely inferable from large-scale reconstructions and that is representative of local environmental factors or ecological niches.

Located in the southern Rhaetian Alps, a key area from a glaciological and a climatic point of view, the site named *Bosco Antico*, literally meaning "ancient wood", represents an extremely important natural archive of environmental information preserved in European larches (*Larix decidua* Mill.). This fascinating forest has been inhabited since the Bronze Age and was almost certainly heavily harvested during the 11th and the 15th centuries (Backmeroff, 2001). In fact, there is evidence that its trees were used to make charcoal to feed the iron furnaces in the area (Backmeroff, 2001; Backmeroff, 2013). Nevertheless, a chronology of this wood was never investigated from a dendroclimatic point of view, despite the fact that it can supply climatic information from the last six centuries.

Here, we present new data derived from a key site in the Italian Alps to augment regional climate reconstructions. In particular, we present a site chronology of the *Bosco Antico* and, aiming to assess the suitability of this chronology for climatic purposes, we performed a detailed dendroclimatic analysis using the most accepted methodologies of investigation. Finally, we propose a reconstruction of the summer mean temperature that extends a previous reconstruction performed on the nearby Adamello–Presanella massif (Coppola & *alii*, 2013).

STUDY AREA

The *Bosco Antico* is a high-altitude stand located on the Ortles-Cevedale Group, in Val Comasine, close to the northern slope of the Val di Sole, southern Rhaetian Alps (46°20' °N 10°40' °E, fig. 1); it is known for the longevity of its trees from which it takes its toponym. Studied in the early 1990s, *Bosco Antico* represents the most ancient living wood in the Val di Sole area (Backmeroff, 2001). Dendrochronological analyses were conducted on the largest individuals and on unearthed charcoal, which determined a maximum age of approximately 600 years for the living trees, while buried fragments, belonging to an older period, revealed that humans have frequented these lands for iron mineral extraction since the 10th century (Backmeroff, 2013). The fascinating and peculiar character of this site led to the creation and management of a natural path through the woods to highlight its beauty, its past land uses and the cultural heritage of the area. Nevertheless, the dendrochronological series supplied by this astonishing forest were never used for dendroclimatic purposes.

The sampled stand is located on Late Pleistocene glacial deposits successively developed from a rock glacier that was presumably active during the Late Glacial period and that is presently preserved as a relict landform (Dal Piaz & *alii*, 2006; Chiesa & *alii*, 2012). The deposits originated from metamorphic rocks characterized by biotitic paragneiss

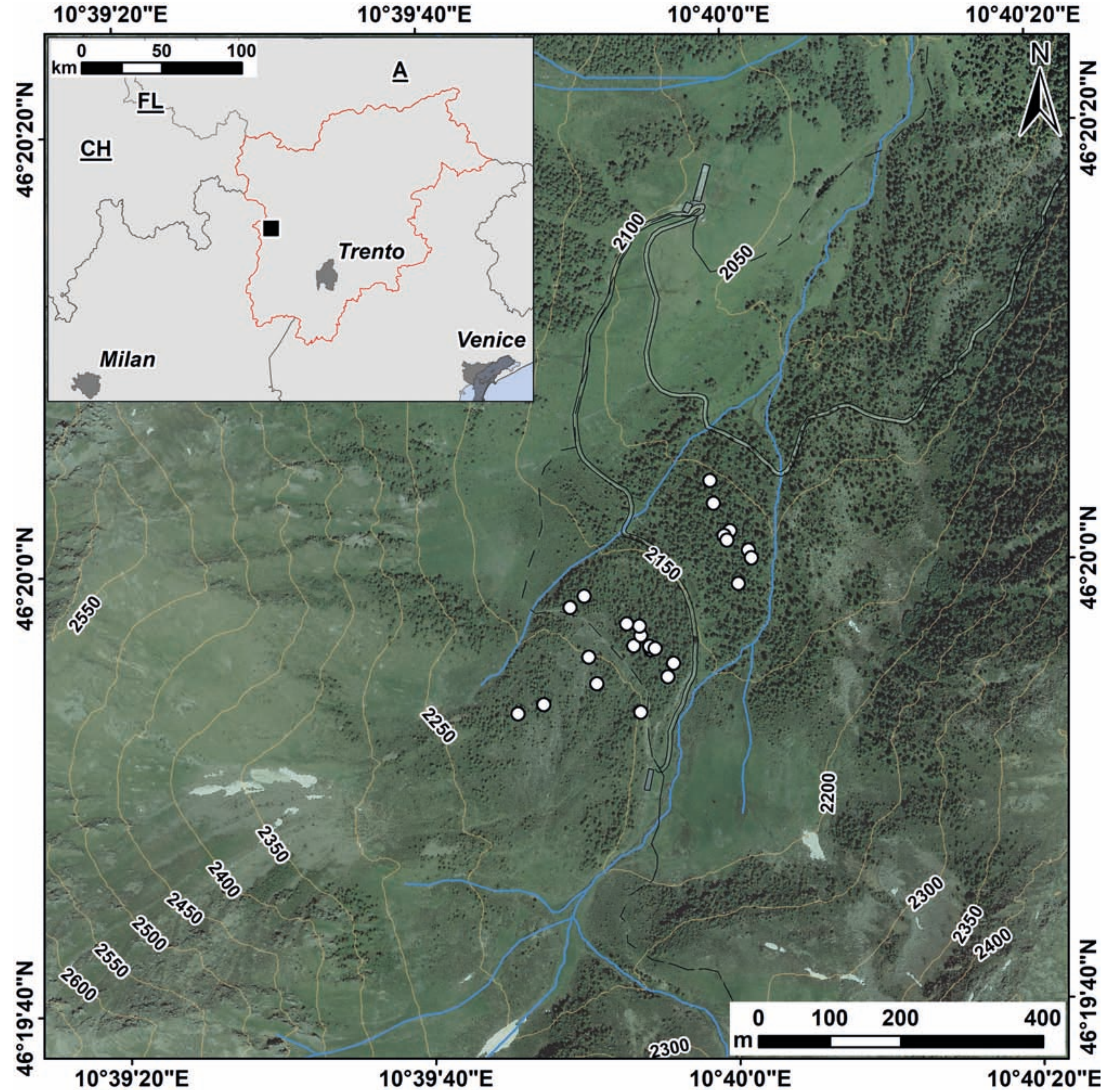

FIG. 1 - Location map of the sampled individuals. The white circles represent the position of the sampled trees, and the black square in the upper-left panel represents the position of the sampled site.

(Scisti del Tonale), marbles and amphibolites belonging to the pre-Permian period (Dal Piaz & *alii*, 2006; Chiesa & *alii*, 2012) which outcrop on the surrounding peaks. The developed soils on these deposits are classified as podzols, cambisols, histosols and umbrisols, depending on the parent material and on the vegetation cover (Galvan & *alii*, 2008). The sampling area is characterized by ancient, dominant larch individuals scattered among ericaceous shrubs, with the relatively young larch trees occupying the higher elevations.

The Alpine Arch, due to its elevation and its location at the intersection of four principal climate regimes, is an area of special climatological interest (Auer & *alii*, 2007; Brunetti & *alii*, 2014; Isotta & *alii*, 2014; Crespi & *alii*, 2018). *Bosco Antico* is located on the southern rim of the Alpine chain, slightly south of the "inner dry alpine zone" and is characterized by a mean annual temperature of approximately 5 °C, as estimated over the 1961-1990 reference period (Brunetti & *alii*, 2006; 2014). The mean annual precipitation, calculated for the same reference period, is approximately 990 mm (Crespi & *alii*, 2018), and the climate of the area is classified as Dbf, "a cold climate without a dry season and warm summer", according to the Köppen-Geiger classification (Peel & *alii*, 2007).

MATERIALS AND METHODS

Tree ring data

A total of 48 cores were extracted from 24 old larch trees. From each tree, two 5.15 mm thick cores were collected using a 500 mm incremental borer (Haglöf, Sweden). To avoid reaction wood, the slope direction was taken into account during the sampling (Schweingruber, 1988).

The cores were glued to wooden supports and then polished using progressively finer sand papers, from P80 to P2000, to emphasize the inter- and intra-annual borders. The earlywood (EW hereafter) and latewood (LW hereafter) widths were measured separately using an incremental slide (LINTAB™ mod. 3, RINNTECH®, Heidelberg, Germany) with a precision of 0.01 mm. TSAPWin Scientific 4.69 h software (RINNTECH®) was used to collect measurements in decadal format. The tree-ring width series (TRW) were calculated as sums of EW and LW and then visually compared and cross-dated with the other series from the same site. The correctness of the dating was checked by means of a second, visual cross-dating using a reference larch chronology (Bebber, 1990), and the consistency of the cross-dating was statistically checked using COFECHA software (Holmes, 1983; Grissino-Mayer, 2001). Then, all the series belonging to the same individual were averaged to create the individual series.

To obtain a chronology suitable for dendroclimatological analysis, all the trends not related to the climate should be attenuated. With this aim, the series were standardized by applying a modified negative exponential curve or a negative/horizontal line when the first method did not properly represent the tree growth (Cook & Kairiûkštis, 1990). Other standardization methods (Cubic smoothing splines with a stiffness of 100, 200 and 300 years) were used as a comparison, but the modified negative exponential method most often preserved the mid-term trend, especially in the final portion of the chronologies. The variance was stabilized by means of a power transformation (Cook & Peters, 1997). These conservative methods allowed for the preservation of the mid- to short-term trends (Cook & Kairiûkštis, 1990; Melvin, 2004). The variance stabilization and the standardization of the TRW, EW and LW series were performed using the dplR package (Bunn, 2008; 2010) of the R project statistical environment (R Core Team, 2018). Ring-width index series for the EW, the LW and the TRW were calculated as a ratio of the observed indexes to the hypothetical growth curve. The mean site standard (S-* hereafter) and residual (R-* hereafter) chronologies were built by bi-weighting and pre-whitening the indexes series.

Due to the uneven sample depth, the expressed population signal (EPS; Wigley & *alii*, 1984) value was used to determine the portion of the chronologies with a strong common signal. Despite new discussions on the usage of this parameter in dendroclimatology (Buras, 2017), the commonly used EPS threshold of 0.85 was employed to subset the S-* and R-* chronologies, even if the subsample signal strength (SSS) presented higher values than the proposed threshold (Wigley & *alii*, 1984). The EPS, the SSS and the inter-series correlation (r_{bt}) were calculated on a moving window of 50 years with 1-year step using the dplR package.

Meteorological data

The global and regional climatological datasets that are commonly used to obtain climate information are based on sparse stations and lack representativeness at the local scale, especially for remote sites. This scenarios is even more true if we go back to the 19th century, or earlier. For this reason, we reconstructed the climate information for the specific sampling site in a more accurate way. Specifically, long-term monthly meteorological series were reconstructed to be representative of the specific site (10.65409 E 46.33300 N and 2008 m a.s.l.) by exploiting the large amount of long instrumental meteorological series available for Italy and the surrounding areas and interpolating the climate information provided by station data by means of the anomaly method (New & *alii*, 2000; Mitchell & Jones, 2005), as described in Brunetti & *alii* (2012). The interpolated temperature series spans the period from 1774 to 2016, whereas the precipitation series were reconstructed from 1800 to 2016. Both S- and R-series were considered for the chronologies and the climate variables.

Chronologies and climate relationship

The growth-climate relationship was assessed by calculating the Pearson's correlation indexes between the R-chronologies and the climatic parameters. The correlation indexes were calculated over the whole period covered by the datasets and the months starting from May of the prior year to October of the current growth year, for a total of 18 months. In addition, seasonal variables were created and investigated by averaging the monthly climatic parameters from two, three and four months.

The stability of the growth-climate relationship over time was verified by means of a moving correlation analysis, performed year-by-year, using a window width of 50 years. All the correlations were calculated in the R statistical environment by means of the "treeclim" package, applying the bootstrapping procedure described in DENDROCLIM2002 (Biondi & Waikul, 2004; Zang & Biondi, 2015; R Core Team, 2018).

Climatic reconstruction

The split-calibration process was applied as described in Coppola & *alii* (2013), and the reliability of the reconstruction was checked by means of several statistical parameters: the reduction of error (RE), the coefficient of efficiency (CE), the autocorrelation of the residuals (by means of the Durbin-Watson test, DW) and their distribution (Cook & *alii*, 1994). The climatic predictands were chosen on the basis of the results of all the previous analyses to reduce the uncertainties in the final anomalies reconstruction. The temperature reconstruction was obtained by means of a linear regression model between the climatic anomalies (predictands) and the tree-ring chronologies (predictors).

RESULTS

Chronologies

A total of 16,631 rings on 48 cores were measured. The cores belonging to the same tree were averaged to create individual series, and then, 8734 rings belonging to 24 individuals were analysed. The chronologies cover 596 years, from 1420 to 2015 A.D., and the longest portion with an EPS > 0.85 spans from 1520 to 2015, for a total of 496 years. The EW represents 76 ± 4% of the TRW, whereas the LW represents 23 ± 4% of the TRW. The total EPS values are far beyond the commonly used threshold of 0.85, being 0.962, 0.958 and 0.951 for the TRW, EW and LW chronologies, respectively, revealing the presence of a strong common signal. Autocorrelation in the standardized series is relatively high, with a mean of 0.76 ± 0.10, 0.71 ± 0.11 and 0.74 ± 0.10 for TRW, EW and LW, respectively; thus, autocorrelation deprived residual chronologies (R-*), showing values of -0.05, -0.05 and 0.01, respectively, were preferred in the correlation analysis. Summary information is reported in table 1, and z-scored chronologies, EPS and sample depths are shown in fig. 2.

TABLE 1 - Bosco Antico chronology statistical parameters. EPS = Expressed Population Signal; r_{bt} = inter-series correlation; MS = mean sensitivity; AR = 1st order autoregressive model; σ = standard deviation.

Mean Chronology	Span [EPS > 0.85]	Length	Total EPS	r_{bt} (σ)	MS (σ)	AR (σ)
S-TRW	1420 – 2015 [1520 – 2015]	596 [496]	0.962	0.755 (0.059)	0.228 (0.044)	0.759 (0.099)
S-EW	1420 – 2015 [1531 – 2015]	596 [485]	0.958	0.746 (0.067)	0.292 (0.051)	0.712 (0.108)
S-LW	1420 – 2015 [1524 – 2015]	596 [492]	0.951	0.639 (0.066)	0.349 (0.040)	0.741 (0.104)

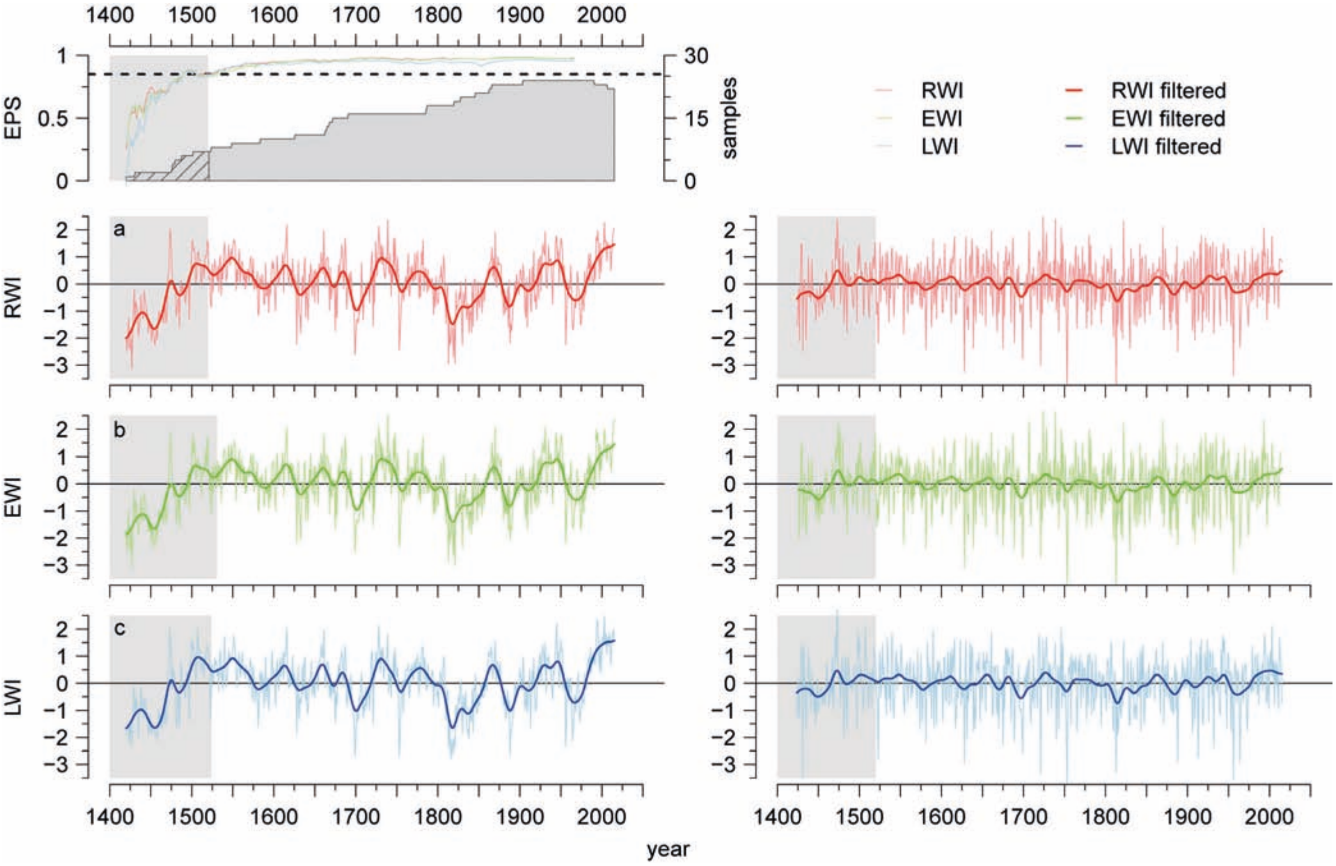

FIG. 2 - Upper panel: Expressed population signal (EPS). Lower panels: z-scored indexes (thin line) and 31-years gaussian filtered chronology (thick line) for standard (left) and residual (right) tree-ring index (a), earlywood index (b) and latewood index (c) chronologies. Sample depth is relative to all chronologies.

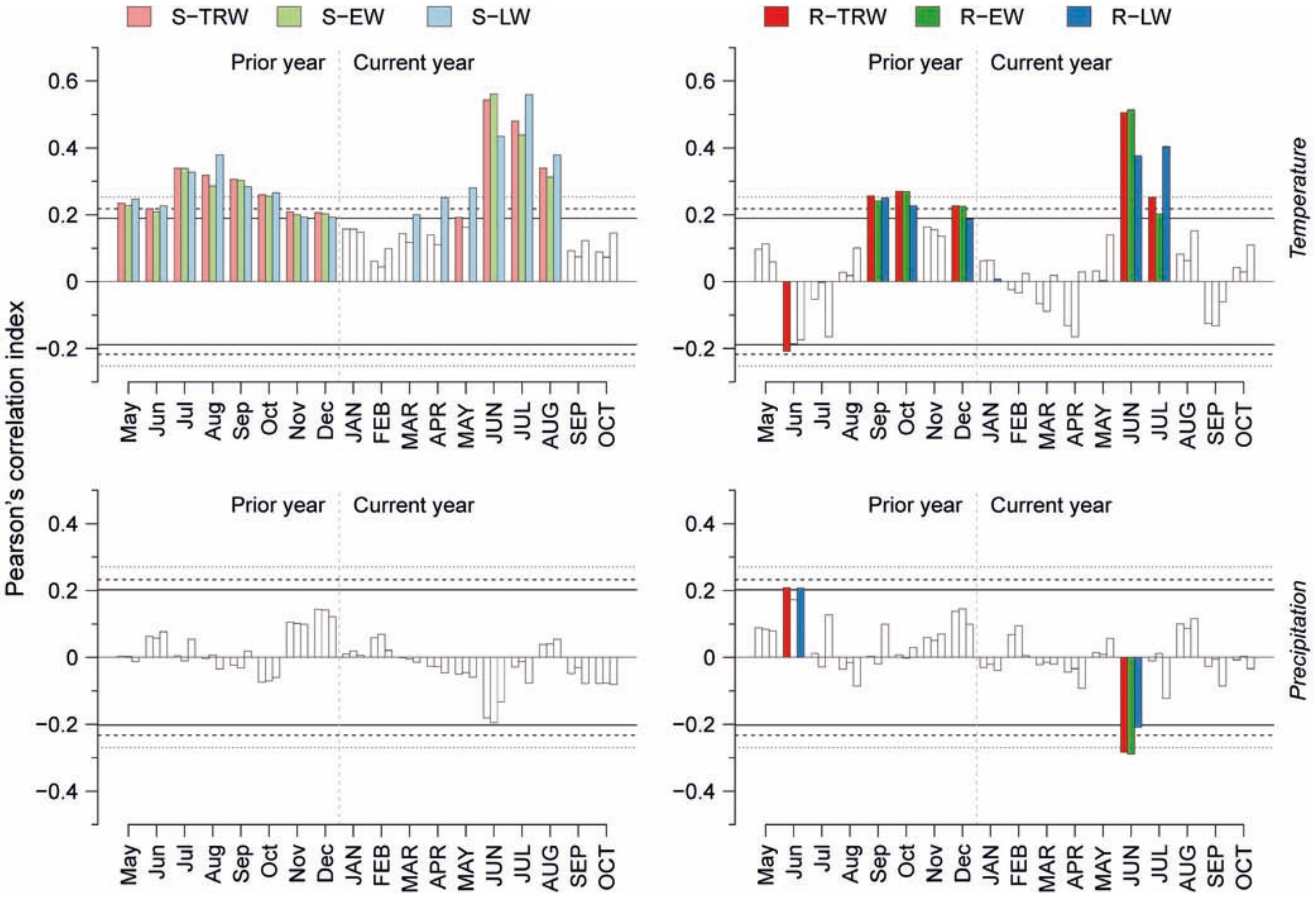

FIG. 3 - Correlation indexes between temperature or precipitation datasets and S-* (left panels) or R-chronologies (right panels) of TRW (red), EW (green) and LW (blue). Coloured bars identify significant correlation values at 95%.

Standard climatic analysis

The correlation function analysis between R-* and the residual temperatures dataset returned similar results for all the chronologies. All the resulting R-chronologies were influenced by prior September, October and December temperatures, whereas for the current growing season, all were influenced by the mean temperatures of June and July (fig. 3). Specifically, R-TRW and R-EW correlate much better with June than R-LW does, whereas on the other end, R-LW is better correlated with July temperatures than R-TRW and R-EW, which show lower values than for June. Regarding precipitation, a significant negative correlation between R-chronologies and the current June is observed, with R-TRW and R-EW returning more negative values than R-LW. Moreover, R-TRW and R-LW are slightly positively correlated with June precipitation of the prior growing season (fig. 3).

The correlations between the S-chronologies and the meteorological series are nearly always positively correlated, denoting a large influence of the mid-term variability (sensu Melvin, 2004) on the tree-growth. The seasonal correlations show an influence of previous winter and current summer temperatures on the R-chronologies (fig. 4). Moreover, previous winter temperatures are more highly correlated with the R-TRW and R-EW than with R-LW; in contrast, summer temperature correlates better with R-LW than with R-TRW and R-EW. Regarding the S-chronologies, current summer aggregated temperatures show higher correlation values than those observed with the prior winter, whereas the spring aggregated temperatures show the lowest correlation values (fig. 4). The seasonal correlations between tree-ring chronologies and precipitation show no significant correlation values or either S- or R-chronologies, which is in agreement with the current knowledge (fig. 4). Because of the lack of correlation, precipitation was not considered in further analysis.

The moving correlation analysis performed on the seasonally aggregated temperatures highlights a high stability in the 2-month aggregated temperatures; R-TRW and R-EW show high values of correlation with the early summer temperatures of June-July (JJ), whereas no significant correlation values are reported with the mean temperature of July-August (JA). In contrast, R-LW shows significant values of correlation with both JJ and JA mean temperatures (fig. 5a). For the 3-month correlation, all the chronol-

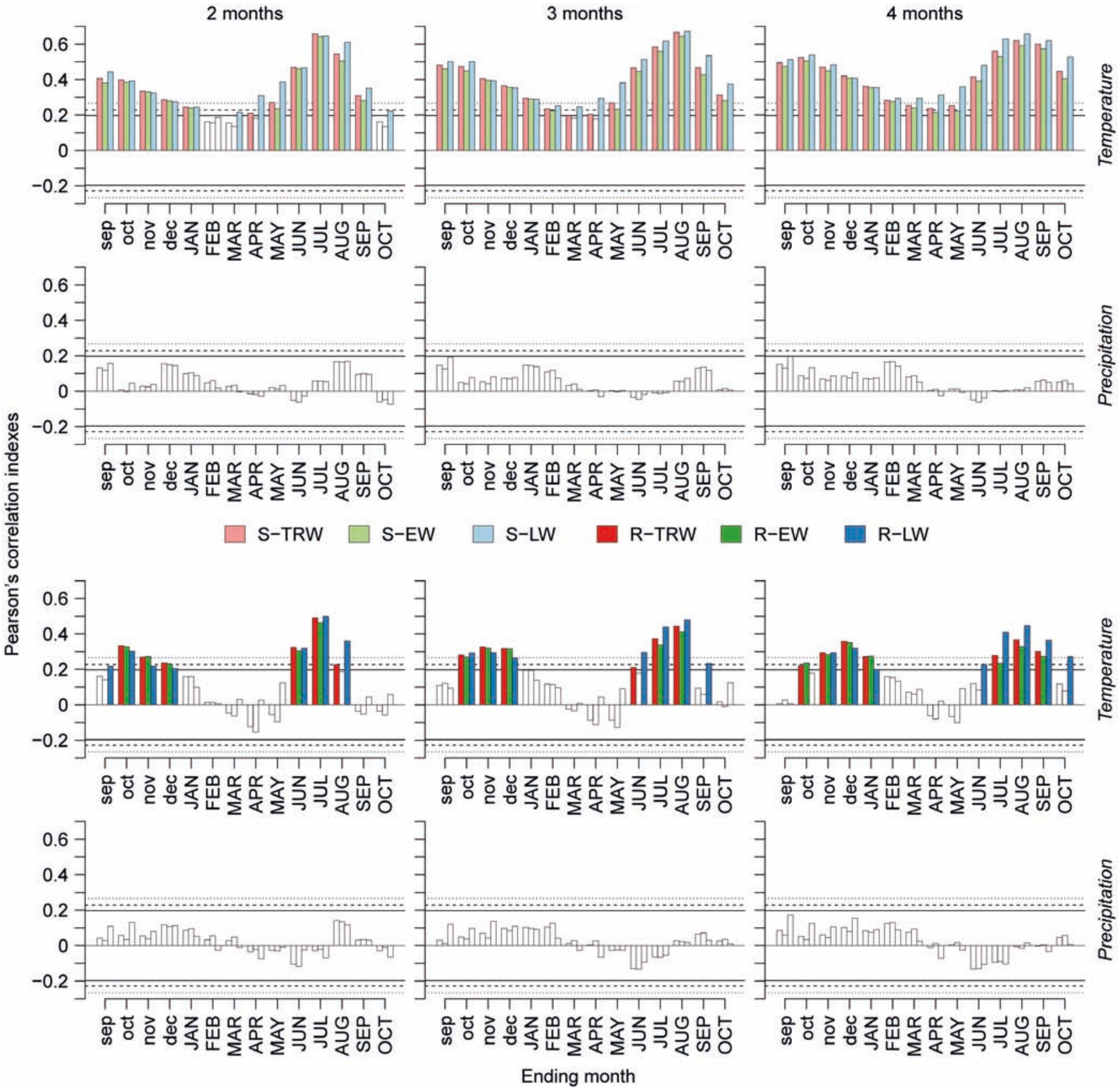

FIG. 4 - Seasonal correlation indexes between the aggregated variables of temperatures or precipitation and S-* (upper panels) or R-* (lower panels) chronologies. The months reported on the x-axes represent the last month of each considered window. Horizontal non-zero solid, dashed and dotted lines represent the significance level at $p < 0.05$, 0.01 and 0.001, respectively. Coloured bars identify correlation values significant at 95%.

ogies show a very stable recorded June-August (JJA) signal, with slightly better results for R-LW. These outcomes perfectly agree with the static correlation analysis results. The R-TRW correlation values show trends that perfectly represent the mixture of the two components, R-LW and R-EW, with a stronger influence of the signal recorded by the R-EW. The S-chronologies show similar results in the oldest portions, but reveal an opposite trend in the most recent half, which is characterized by the strongest mid-term trend of the time-series. Furthermore, the S-chronologies also show a more stable climatic signal with the longest monthly window (fig. 5b).

Calibration and reconstruction

Based on previous results, prediction capabilities of the chronologies for climatic reconstruction were checked only for those climatic variables showing the highest correlation values and stability over time. Then, the 2-month (JJ) and the 3-month (JJA) average temperatures were selected as predictands. The results of the split-calibration procedure

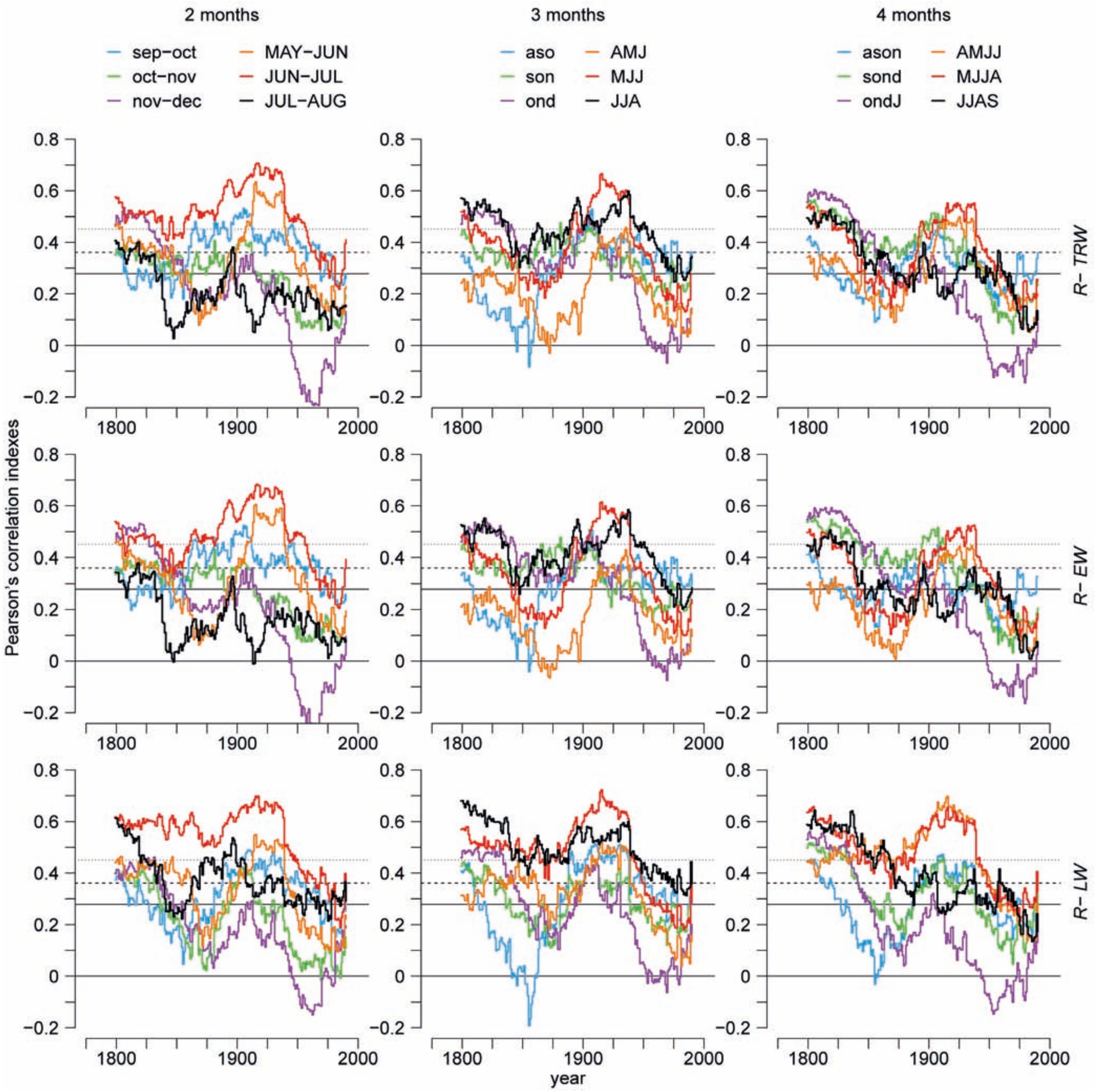

FIG. 5a - Moving correlation values between R-chronologies and the aggregated temperatures of different windows. Horizontal non-zero solid, dashed and dotted lines represent the significance level at $p < 0.05$, 0.01 and 0.001, respectively.

performed on the R-chronologies are summarized in table 2. The correlation values obtained for the 2-month variable are generally higher than those obtained using the 3-month variable, and the best prediction capability is obtained when using the R-LW as predictor. The highest values of r^2, when considering the whole period (1768–1960), are calculated for JJ temperatures, whereas JJA returns a slightly lower value. The highest values of RE and CE are obtained when calibrating the regression on the first half-period (the JJ temperatures), whereas when considering the JJA temperatures, better results are obtained using the second half-period as the calibration window. The DW test highlights a significant positive autocorrelation only when considering the regression residuals obtained by the JJ reconstruction, calibrated on the first half-period. However, even if the JJ regression calibrated on the 1867–1960 period shows slightly lower RE and CE values, it presents no autocorrelation in the regression residuals (DW = 2.021; table

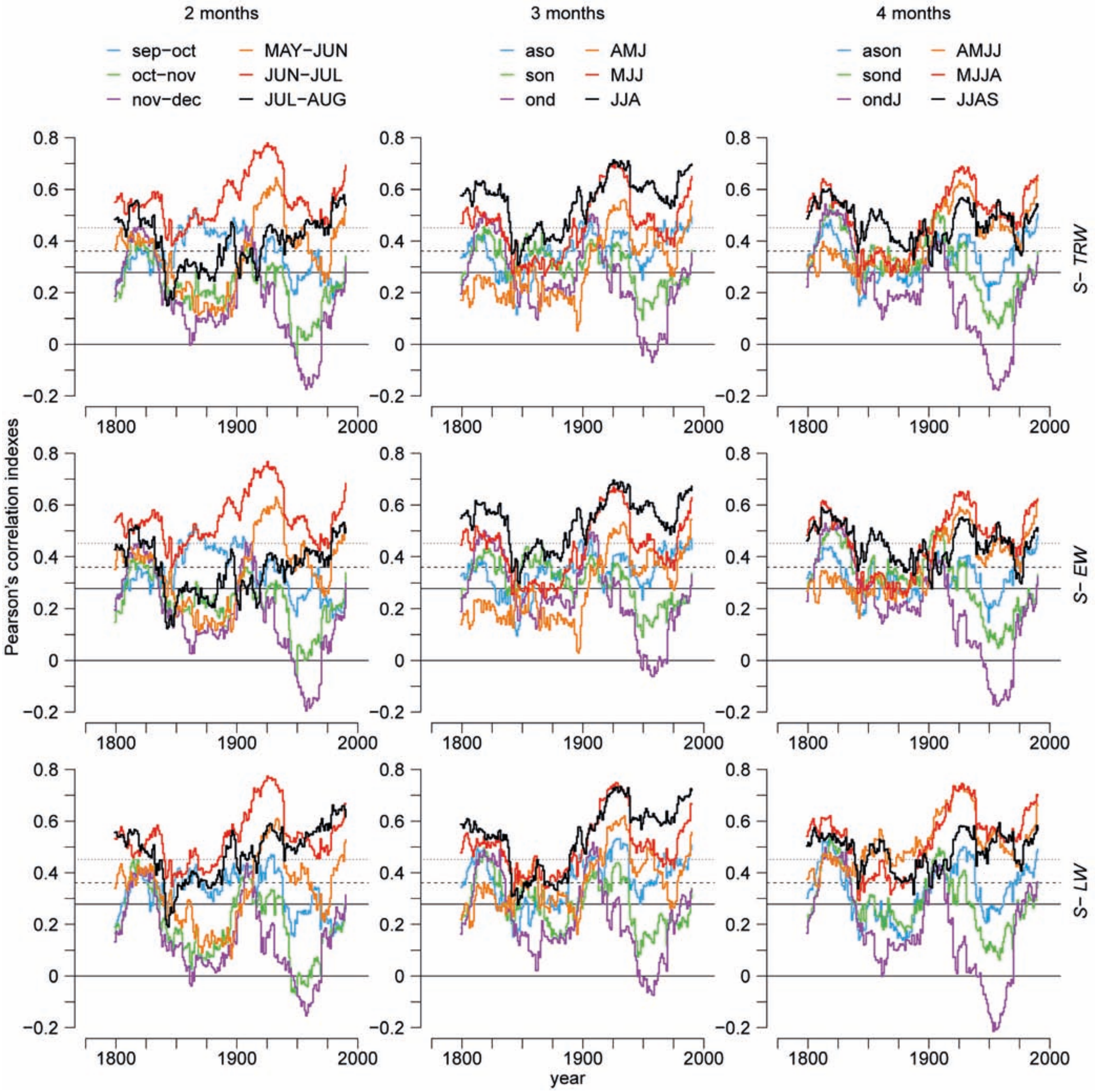

FIG. 5b - Moving correlation values between S-chronologies and the aggregated temperatures of different windows. Horizontal non-zero solid, dashed and dotted lines represent the significance level at $p < 0.05$, 0.01 and 0.001, respectively.

2), and thus, its regression coefficients were used to reconstruct the temperatures. The temperature reconstruction is performed by applying the regression coefficients obtained by the calibration of R-LW to the S-LW to retain part of the mid-term variability in the final output.

The reconstructed JJ anomalies series spans between 1525 and 2015, presenting values between -2.3 and +1.9 °C, equivalent to temperatures between 6.2 and 10.4 °C (fig. 6). Due to the excellent visual and statistical correlation between our reconstruction and the interpolated temperature anomalies (table 2), the JJ reconstruction back to A.D. 1525 can be considered reliable. This result is also confirmed by the high correlation values obtained when comparing the unfiltered and the filtered variability values of our reconstruction with others proposed for the surrounding areas (Coppola & *alii*, 2013), as well as for the whole Alpine Arch (table 3; Büntgen & *alii*, 2011; Trachsel & *alii*, 2012). In analysing the series, the strongest minimum is reported in 1816

TABLE 2 - Climatic inference abilities of Bosco Antico chronologies related to the 2-months June-July (round bracket) and the 3-months June-August.

Calibration			Verification				Full period
	r^2	DW		RE	CE	RMSE	r^2
R-TRW							
1774 - 1867	(0.241)	(1.87)	1868 - 1960	(0.383)	(0.383)	(0.052)	(0.303)
	0.207	1.995		0.273	0.273	0.045	0.235
1867 - 1960	(0.388)	(2.193)	1774 - 1866	(0.236)	(0.236)	(0.054)	(0.303)
	0.286	2.066		0.201	0.201	0.033	0.235
R-EW							
1774 - 1867	(0.192)	(1.934)	1868 - 1960	(0.353)	(0.353)	(0.047)	(0.262)
	0.167	2.031		0.256	0.256	0.041	0.202
1867 - 1960	(0.359)	(2.264)	1774 - 1866	(0.186)	(0.186)	(0.055)	(0.262)
	0.263	2.086		0.163	0.163	0.033	0.202
R-LW							
1774 - 1867	(0.351)	*(1.583)*	1868 - 1960	(0.339)	(0.339)	(0.064)	(0.354)
	0.336	1.759		0.189	0.189	0.058	0.303
1867 - 1960	(0.374)	(2.021)	1774 - 1866	(0.331)	(0.331)	(0.049)	(0.354)
	0.291	2.05		0.289	0.289	0.03	0.303

r^2: Explained variance, DW: Durbin-Watson statistic, RE: reduction of error, CE: coefficient of efficiency, RMSE: root mean squared error. *Italicized* DW values show significant autocorrelation in the regression residuals at $p < 0.05$.

TABLE 3 - Correlation between S-LW based temperature anomalies and published reconstructions. Column headers specify the length of the applied cubic smoothing spline (50% variance cut off).

	Not filtered	10 years	20 years	30 years
Büntgen2011	0.66	0.67	0.71	0.73
Trachsel2012	0.59	0.60	0.62	0.61
Coppola2013	0.68	0.64	0.64	0.64

Büntgen2011: Büntgen & *alii*, 2011; Trachsel2012: Trachsel & *alii*, 2012; Coppola2013: Coppola & *alii*, 2013. Correlation values with Trachsel & *alii*, (2012) calculated using the reconstruction values obtained by the Variant6.

(-2.3 °C), from which upward trends are noticeable towards both the past and the present. Cool phases are noticeable i) around 1700, ii) in the first half of the 19th century, iii) around 1900 and iv) during the 1970s. The warmer phases occurred in i) the 1730s, ii) the 1940s and iii) since the 1980s.

DISCUSSION

Bosco Antico is the most ancient living wood in the Val di Sole area and among the oldest living stands in the Italian Alps. The performed analyses show a high mean sensitivity value, even if the results are slightly lower than those reported for the same species in other sites (Carrer & Urbinati, 2006), and include a high inter-series correlation value that exceeds those previously reported (Carrer & Urbinati, 2006), with a strong common signal between individuals (Wigley & *alii*, 1984). The mean summer temperatures act as the main limiting factor for tree growth, as demonstrated by the highest correlation values calculated for this period (fig. 3; fig. 4; fig. 5). The high sensitivity to the climate is likely to be determined by the age of the sampled trees. In fact, a previous study demonstrated that the growth of the European larch is mainly driven by climate and that the older tree age-classes are more sensitive to climatic parameters. The use of tree-ring series from old individuals promotes the attenuation of the noise that characterizes tree growth in its initial phases and enhances the retained climatic signal (Carrer & Urbinati, 2004).

The use of composite chronologies makes it possible to analyse the intra-annual relationships between climate parameters and different wood structures (Koprowski, 2012). Interestingly, the correlation analysis revealed that June temperatures have an influence on the EW growth whereas July temperatures mainly influence the LW growth (fig. 3). These outcomes are in agreement with previous results, which reported a significant correlation between June temperatures and TRW chronologies, although a more stable signal over time can be obtained by considering the mean seasonal temperatures of June, July and August (Coppola & *alii*, 2012; 2013).

Even though temperature acts as the main limiting factor of tree-growth, the short-term correlation values obtained with this climate parameter are affected by a decrease in the most recent period (fig. 5a). This effect is noticeable only when considering the year-to-year variability (fig. 5) that is widely independent from the type of standardization used to attenuate the age trend. Despite the fact that the decoupling effect could partially be due to the site's aspect and elevation (Leonelli & *alii*, 2009), it is more likely the effect of the divergence problem (DP), a well-known issue that affects tree-ring chronologies at a hemispherical and regional scale (D'Arrigo & *alii*, 2008), as well as locally (Coppola & *alii*, 2012). DP is recorded as a high-frequency loss in climate sensitivity and/or low-frequency trend offset (Büntgen & *alii*, 2008), evidenced by lower correlation values with a growth-limiting parameter (Wilson & *alii*, 2007). Several factors may either

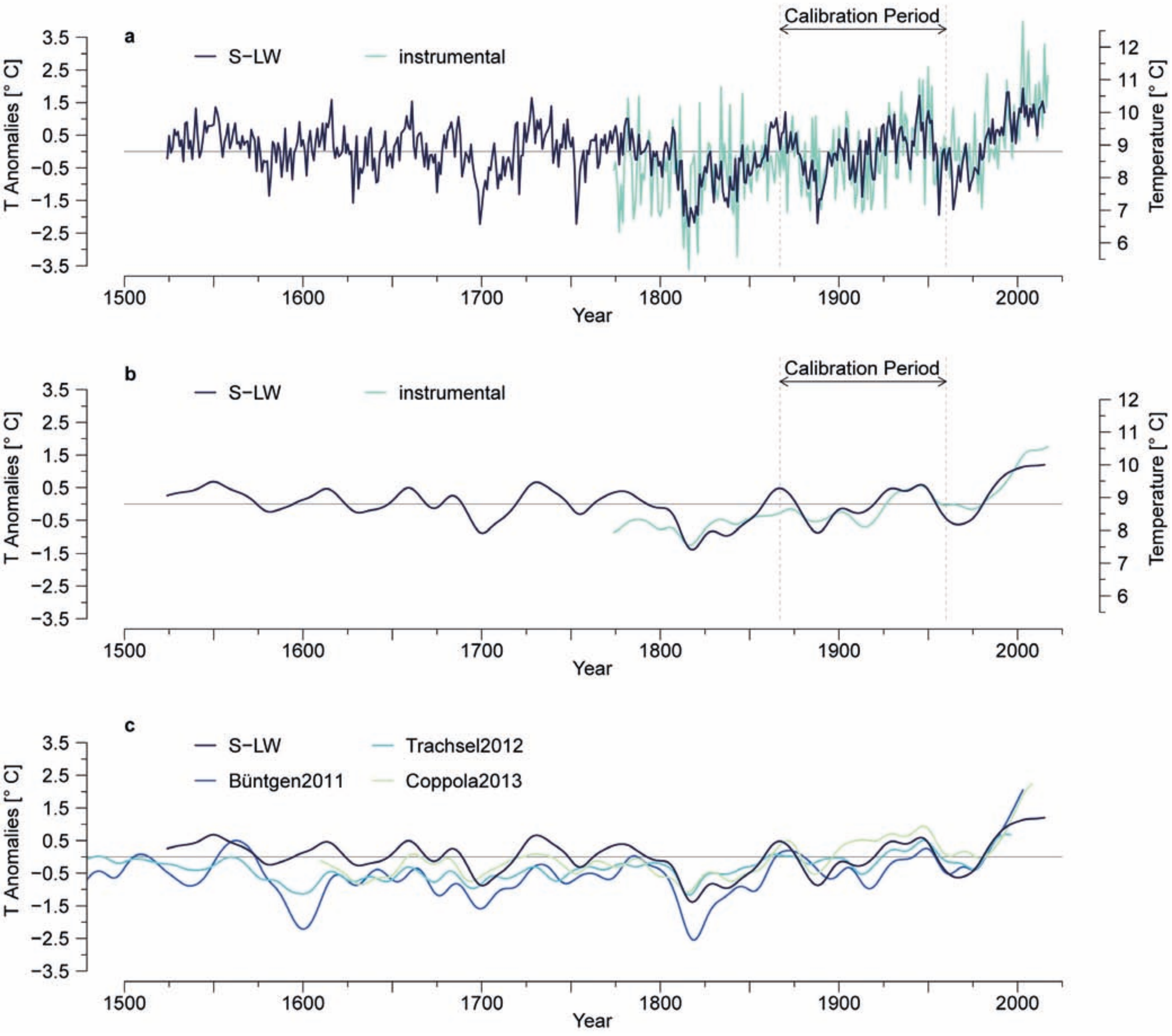

FIG. 6 - Yearly S-LW based reconstructed June-July temperature anomalies using the 1867-1960 calibration period (a) and the 31-years Gaussian filtered series (b). Comparison between Bosco Antico S-LW based reconstructed June-July temperature anomalies and previously published reconstructions (c; references in table 3).

enhance or attenuate this phenomenon (D'Arrigo & *alii*, 2008), resulting in a non-ubiquitous issue (Leonelli & *alii*, 2016) that must be addressed at the local to regional levels (Büntgen & *alii*, 2008). In the *Bosco Antico* chronologies, the DP is evident in the most recent portion of the R-chronologies (fig. 5a), whereas the S-chronologies show an increase in correlation values that testify to a coherence between the trend of tree radial growth and the trend of the mean summer temperatures, even in the last decades (fig. 5b). Nevertheless, in the S-chronologies, a slight trend offset, attributable to the DP, has been noticeable since the 1990s (fig. 6).

Climate reconstruction

The reconstructed JJ temperature series show the most negative minimum in 1816, also known as the "year without a summer" (Skeen, 1981; Brugnara & *alii*, 2012). It represents the coldest summer in the analysed period and occurred during one of the last pulses of the Little Ice Age, a phase of climatic deterioration that is supposed to have ended around the 1850s in the Adamello-Presanella Group (Baroni & Carton, 1990; 1996). A strong contribution to the temperature decrease in 1816 comes from the Tambora explosion, one of the most famous and intense explosion of the entire modern era (Volcanic Explosion Index: VEI = 7, Cole-Dai & *alii*, 2009). This paroxysmal event ended on July 15, 1815, and injected into the stratosphere more than 100 km^3 of materials (dust and volatiles). The emitted products reflected part of the incoming solar energy, causing strong temperature reductions during the following summer in the Northern Hemisphere. Nevertheless, the 1800 pulse, which is driven by a well-known solar activity minimum, called the Dalton minimum (Wagner & Zorita, 2005; Usoskin, 2017), does not represent the maximum expression of the Little Ice Age, a period characterized by low summer temperatures, in the area.

Another relevant minimum occurred in approximately 1699 and presumably represents, locally, the period that temperatures were dropping at the highest rate, driven by the sun stasis known as the Maunder minimum (Eddy, 1976), a phase lasting 80 years and characterized by the total absence of Sun spots (Usoskin, 2017). In fact, this minimum concludes a century characterized by cool and cold temperatures during which the maximum Holocene glacial extent of the nearer La Mare Glacier occurred (Carturan & *alii*, 2014; Baroni & *alii*, 2017b). The diachronicity between the maximum advances of the glaciers in the area (occurring during the 1650s confirmed by geomorphological evidence) and the reconstructed temperatures (that highlight more negative anomalies at the beginning of the 18th century than during the 17th; fig. 6) could suggest that during the first half of the 17th century, cool and wet climatic conditions affected the area, causing a large advance in the ice bodies, whereas at the beginning of the 18th century, drier conditions may have occurred, attenuating the advancement of the glaciers more than the previous pulse.

The reconstructed JJ temperatures highlighted two other significant minima: 1753 and 1888. These minima appear to be synchronous with larch budmoth (LBM; *Zeiraphera diniana* Gn.) outbreaks that cyclically affected the larches. Thus, the 1753 and 1888 minima may be the results of a mixed effect of cool temperatures and LBM since in those years, strong LBM outbreaks are reported in sites close to the study area (Büntgen & *alii*, 2009). Although the Bosco Antico chronologies seem to be affected by the LBM, no evidence of the typical cycle of this Lepidoptera, which usually occurs every 7-9 years, is present; still, the outbreaks could influence the chronologies sporadically. In a comparison of the R-TRW from the study site with a Swiss stone pine (*Pinus cembra* L.), the R-TRW chronology built for the near valley of Val di La Mare (located 5 km northeast) highlights an anomalous and significant reduction in larch growth during the years 1814, 1831, 1889, 1956 and 1964 (considering the period between 1800 and 2015). These reported years were identified as potentially characterized by an LBM outbreak. These anomalous years are largely in agreement with the major outbreaks reported in the site's area by a previous study (Büntgen & *alii*, 2009), with the exception of 1831, which was the year after a massive LBM outbreak. Because of the LBM outbreaks, the temperature reconstructions obtained for those years are broadly questionable, but due to the rare occurrence of these events, neither the general trend nor, consequently, the general climatic reconstruction were affected.

In the analysis of the reconstructed temperatures since 1816, a strong but non-homogeneous increasing trend is detected, interrupted by two major phases of negative anomalies: i) around 1900 and ii) during the 1970s (fig. 6). The former phase can be attributed to the Damon minimum, another sun activity stasis (Corona & *alii*, 2010) recorded in other proxy data (Lirer & *alii*, 2014). The second phase characterized by negative anomalies is more recent, occurring during the 1970s, with negative reconstructed anomalies from 1950 to 1980 and a mean value of approximately -0.5 °C. This climatic deterioration perfectly matches with the last re-advancement of the glacier fronts registered and described in the area (Citterio & *alii*, 2007; Carturan & *alii*, 2013; Salvatore & *alii*, 2015).

In the reconstructed trend before 1699, the anomalies oscillate around zero, showing cooler periods during the 1580s and in the first half of the 17th century (fig. 6b). Our reconstruction is consistent with the others already proposed for the area (Coppola & *alii*, 2013), but it slightly underestimates the negative anomalies that occurred before the 18th century in comparison to the alpine temperature reconstructions (Büntgen & *alii*, 2011; Trachsel & *alii*, 2012). Moreover, no evidence of the minimum that occurred around 1600 is present (fig. 6c). An explanation for the underestimation of the negative anomalies can be found in the detrending methods used. In fact, even if a highly conservative detrend procedure was applied, part of the mid- and long-term variability was necessarily removed (fig. 6c; Fritts, 1976; Melvin, 2004). The applied standardizing method could have added a bias at the start of the chronologies, causing a slight upward shift in the standardized values. Despite this possibility, the modified negative exponential curve remains the most applicable to the investigated dataset, the most suitable compromise between attenuating the age-effect and preserving the mid-term trend, and among the most commonly used methods. Another explanation for this positive bias, as well as for the missing 1600 cool phase, can be found in the indirect anthropic impact. In fact, as a consequence of the intense harvesting that happened during the 15th century, only the youngest trees survived. This scenario may have caused a decrease in intraspecific competition, resulting in synchronous tree growth release. The successive land uses (pasture and grazing) could have contributed to the maintenance of the area as a competition-free site. This further bias could be an alternative cause of the limited negative fluctuation in the reconstructed temperature around the beginning of the 17th century, just before of the most extensive recorded Holocene advancement of one of the glaciers in the area (Carturan & *alii*, 2014).

CONCLUSIONS

The growth of the European larch in treeline ecotones is mainly driven by June to August temperatures. This well-known climate/growth relationship made it possible to use this species as a proxy for the reconstruction of summer temperatures before the use of weather stations. The *Bosco Antico* is one of the most ancient living woods in the southern Rhaetian Alps, and its tree-ring chronology, spanning almost six hundred years from 1420 to 2015, can be used to successfully integrate the local dendrochronological dataset, lengthening it by at least a hundred years. This chronology provides the longest dendroclimatic series ever reconstructed in the Rhaetian Alps with living trees. The moving correlation analysis highlights that before the 1960s, the climatic signal in the chronologies is preserved and stable since the beginning of the availability of instrumental data in 1774, for both year-to-year and mid-term variability.

The reconstruction of the JJ mean temperature performed using the LW chronologies, in comparison to other alpine temperature reconstructions, shows excellent agreement with the short-term variability; therefore, although this method is limited in its ability to retain all the mid-term trends, the potential for the Bosco Antico chronologies to be used as a climatic predictor is demonstrated. Reconstructed temperatures, in fact, show cooler and warmer periods in accordance with previous temperature reconstructions, astronomical and instrumental data, spanning in a range between -2.3 to +1.9 °C, compared to the 1960-90 mean temperature (about between 6.2 and 10.4 °C at the stand elevation). The coldest phase is recorded in the 1810s-20s (mean value of the decade -1.5 °C) representing the lowest minimum of the entire record that underlines the strongest pulse of the Little Ice Age in the area. Cooler phases are also reported in the first half of the 17th century, around 1700, around 1900 and during the 1970s. The negative anomalies recorded in the 1970s slightly predates the last glaciers advance registered in the Alps.

The conservation, protection and enhancement of the ancient woods in the Italian Alps, often threatened by both anthropic and the inevitable climate pressures, is crucial. Safeguarding these long-living trees is a fundamental issue relating to not only to protecting their biological relevance, their natural beauty and their cultural heritage but also preserving a valuable archive of climatic data.

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(Ms. received 08 May 2018, accepted 20 July 2018)