Project of Strategic Interest NEXTDATA
WP1.4
(Coordinator: Valter Maggi, UNIMIB)

D1.4.B Transfer functions to reconstruct temperature and precipitation from tree ring proxies

Proxy records in Paleoclimatology are widely used for estimating past climate conditions over regions and globally (Mann et al., 1998, 2008; Jones et al., 2001; Cook et al., 2004; Moberg et al., 2005), and recently increasing interest is given to the collection of multiproxy data in open database oriented to climate research (e.g., PAGES2k Consortium, 2017; Nextdata-Italy 2k, 2018). As part of the Earth Science disciplines, Paleoclimatology mainly investigates natural archives quantitatively, usually calibrating models over the most recent periods and then extending back in time the climatic reconstructions. In this way, the geological and paleontological records, the glacio-geomorphological evidences, marine cores, ice cores, speleothems, lake varves, pollen-stratigraphical records, tree rings, corals, etc. may be investigated in order to quantitatively reconstruct the past climate. However, objective climatic information can be extracted also from any available human-related source such as historical archives, instrumental meteorological records, farmer's yield notes or notarial deeds. Both natural and anthropogenic archives rely upon a common feature, which is at the basis of any climatic reconstruction: dating of the recorded information. Any archive is usually made up of different strata deposed through time which may lead to complete sequences of relatively dated information. However, absolute dating is mostly desired in any quantitative reconstruction in order to be able to precisely date the sequences of the extracted information at the calendar year, and any archive typically holds specific characteristics that may influence its time resolution also through time, and its time span. Once the characteristics of a given archive are deeply studied, in terms of definition of its inner mechanism and processes acting while the archive is growing and, later, of the environmental conditions acting on it through time when the archive is already built up, then it is possible to perform a climate reconstruction.

One of the first step when approaching a quantitative climate reconstruction, is the detection of the climatic signals recorded in a given archive. In fact, not all the archives hold a climatic signal and, more extensively, we must consider that not all the technological approaches and knowledge are already known and available for investigating any archive in a palaeoclimatological perspective. Over a common period covered also by instrumental data, the detection of a climatic signal recorded can be quantitatively approached with the application of linear models such as correlation and response functions, using climate as predictor variable (x) and a variable from the proxy record as predictand (y). In order to evaluate the signal stability through time (an issue especially affecting the biological archives), also the ‘moving windows’ technique for these functions can be applied, i.e. the functions are defined over sub-periods of a defined time span (windows) that are shifted by 1 year at the time up to the last year available, thus allowing an evaluation of the coefficient’s changes through time (e.g., Biondi and Waikul, 2004).

After the climatic signal is detected, its stability through time assessed and the climatic target for the reconstruction defined, different types of transfer functions can be applied to a variable of a given proxy record (predictor, x) in order to quantitatively estimate the past climate (predictand, y): in the field of linear models, multiple regression and scaling techniques can be applied.

Reconstructing temperatures from tree-ring data

Tree rings are one of the most used terrestrial proxy record in paleoclimate reconstructions. Quantitatively reconstructing temperature from a tree-ring proxy record, needs the assessment of several passages that already start in the field while selecting the right trees and then by applying correct sampling approaches. Tree selection for dendroclimatic purposes definitively follows a non-random approach, because of the need to exclude young trees, tilted trees, damaged trees, closed forests, etc. in a given region. As regards temperatures, usually high-altitude (latitude) areas are selected, in order to enhance the climatic factor in the linear aggregate model of tree growth (Cook, 1990). At these sites, usually heat availability limits tree growth, thus influencing ring widths (the main parameter used in dendrochronology), maximum latewood density (MXD) and stable isotopes in the wood cellulose. The application of cross-dating techniques within site and between sites, allow to eliminate potential dating errors and data validation further pushes for series selection before constructing a site chronology oriented to climate reconstruction (e.g., Leonelli et al., 2016).

The selection of the climate variable to reconstruct, depends on the climate signal recorded in the tree-ring chronology, which can be built in several ways from the individual growth series, according to the type of signal that is looked for. In all cases, the physiological age-related trends are removed while processing the raw series, by applying growth models and commonly-used standardization techniques (Cook et al., 1990).
Typically, tree ring chronologies easily hold high-frequency signals, whereas the low frequency climate variations over centuries may be well preserved by means of the Regional Curve Standardization technique while constructing the tree-ring chronology or the dendroclimatic network (Esper et al., 2003).

Response functions use principal components of climatic variables in multiple regression to specify climate – tree-ring growth relationships:

$$Y = bX + e \qquad (1)$$

i.e.,

$$y_t = b_1 x_{1t} + b_2 x_{2t} + \ldots b_m x_{mt} + b_0 + e_t \qquad (2)$$

where y_t is the predictand (the actual growth) for year t, $x_1 \ldots x_m$ are the predictor variables (the climate variables, such as monthly temperature and/or precipitation) and $b_1 \ldots b_m$ are the associated regression coefficients of the x; b_0 set the equation to the mean of y_t and e_t is the model error (Fritts, 1976). The main interest in using this model lies in the interpretation of the sign and size of the partial regression coefficients associated to the climatic variables, since they indicate the weight and significance of each predictand and the type of climatic signals recorded in the tree-ring chronology.
Instead of response functions, also correlation functions may be used, by calculating the Pearson's correlation coefficient between the chronology and each monthly variable over a common calibration period. The use of correlation coefficients for detecting climatic signals in the tree-ring chronologies is favored for the easier and straightforward interpretation, even though tree-ring data are noisy records derived from complex interactions between climate and the environment (Fritts, 1976), thus suggesting the use, instead, of response functions.

When the same linear model of multiple linear regression is used for reconstructing past climate, the transfer functions have the same structure as the response functions, but the climatic variables are functionally switched with the proxy variables: for transfer functions, in equation (2) the predictand is a climate variable to be reconstructed (often a seasonalized variable), whereas the predictors are the tree-ring chronologies. When applying multiple linear regression transfer functions, the main interest is the model output, i.e. the estimates of the climatic variance for pre-instrumental periods, which is transferred from the chronology variance (Fritts and Swetnam, 1989).

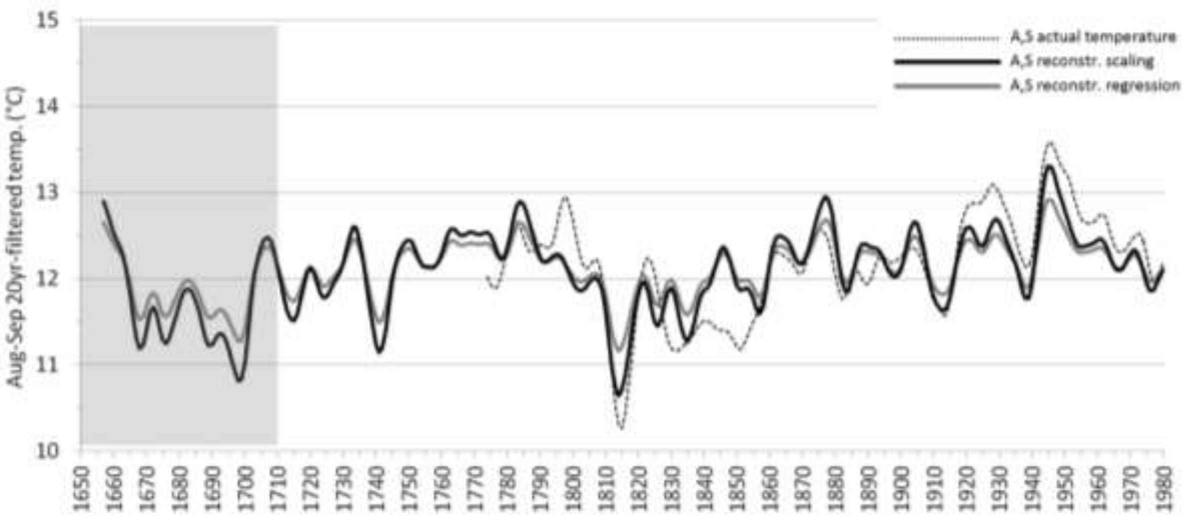

Figure 1. *Reconstruction with regression and scaling approaches of the late summer (August and September) temperature for the Apennines and the southern Italian region up to early 1700s, using a multispecies MXD chronology comprising Abies alba, Pinus*

leucodermis and P. nigra. The series of temperature are low-pass filtered with a 20 yr Gaussian smoother and the gray area depicts the periods prior to 1711, when the conifer MXD chronology used for the reconstruction shows low signal stability (modified from Leonelli et al., 2017).

Using regression-based transfer functions, however, can reduce the climate variance in the reconstructed dataset when the fit between the proxy and climate is lacking (von Storch et al., 2004). Recently in dendroclimatology an innovative approach that tends to better preserve a higher variability in the reconstructed series than regression has been introduced: the linear scaling technique (Esper et al., 2005). Scaling is a technique that sets the dendrochronological series at the same mean and variance of the target climatic dataset. The model calibration is of course performed over the common period between the two dataset, and then a tree-ring based reconstruction of temperature or precipitation for the past, pre-instrumental periods, is performed (Fig. 1).

Before performing a reconstruction, models are calibrated and verificated over different, not-overlapping, time periods belonging to the period covered by instrumental data. Typically, the instrumental dataset is split into calibration and verification periods (Gordon, 1982) and the model performance evaluated by comparing a number of statistics that can be calculated for quantitatively assessing the model quality (e.g. Reduction of Error, Fritts, 1976; Coefficient of Efficiency, Briffa et al., 1988). Calibration statistics in general indicates the model ability in fitting the instrumental data in the dependent set, whereas verification statistics underline how well in the independent set the model predicts the variability of actual independent data (which can be data of the split period for verification, or data being part of other datasets, comprising also already-reconstructed climate series).

Quantitative climate reconstructions from pollen data using pollen-climate calibration models

The basic principle of all quantitative climate reconstructions from biological data is the "methodological uniformitarianism" (Birks and Seppä, 2004, Brewer et al., 2007, Birks et al. 2010) which means, specifically for pollen data, that relationships between modern pollen assemblages and their associated climate conditions can be used as analogue or model to infer past conditions because those relationships have not changed throughout time. In figure 2 it is schematized the uniformitarianism principle and the major requirement, namely, the existence of a modern calibration set composed by modern pollen assemblages and associated climate variables (ie temperature, precipitation).

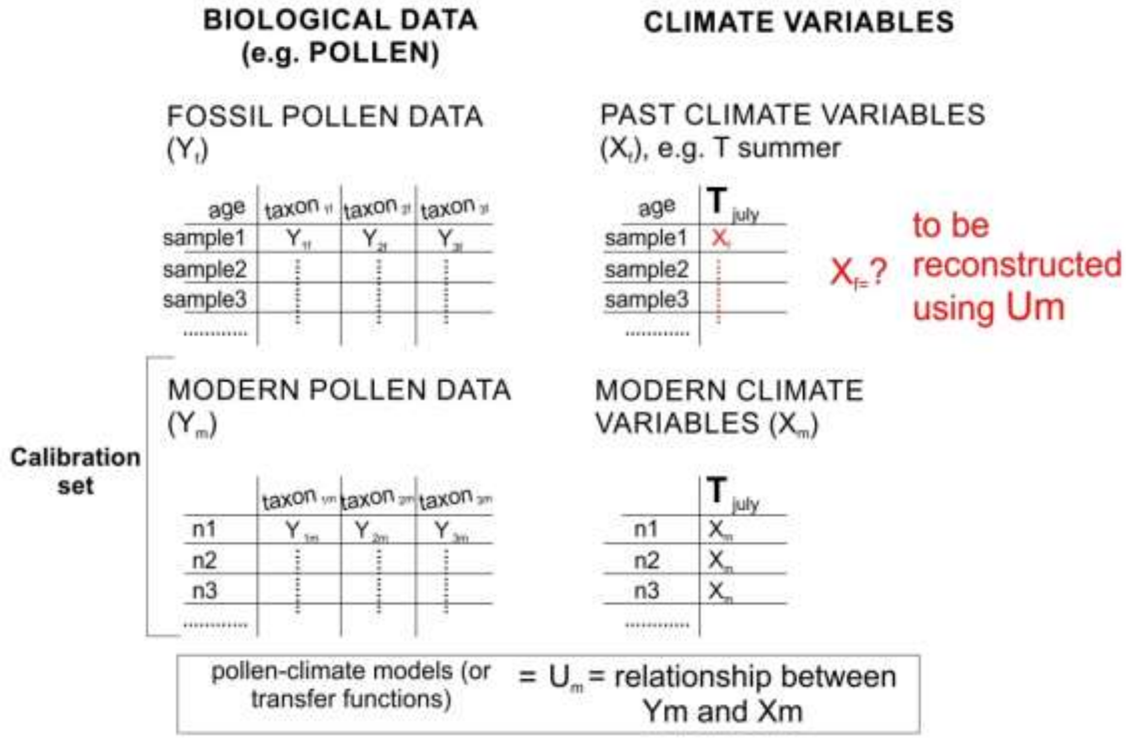

Figure 2: *scheme of the basic principles for quantitative climate reconstructions from pollen data. Y are pollen taxon abundances (percentages), X are climate variables.* X_f*, the unknown climatic variable, to be reconstructed from fossil pollen samples (sum of all taxa* Y_f*), the essential role of a modern calibration set consisting of n= modern pollen assemblages (sum of all taxa,* Y_m*) and associated climate values, and the resulting transfer function (*U_m*) (modified from Birks and Seppä, 2004 and Birks et al. 2010).*

A three-steps approach (Juggins and Birks, 2012) was followed to obtain quantitative estimates of summer temperatures from fossil pollen records in northern Italy. As a first step we developed a modern pollen-climate calibration set that maximized the significance of T summer as explaining variable of the modern pollen assemblages variance. 268 modern pollen samples have been selected from the European Modern Pollen Database (EMPD, Davis et al., 2013) (Fig. 3) ; each sampling location was associated to site-specific instrumental temperature series, computed for the period 1951-2010 from Michele Brunetti. From the time series, mean values have been calculated and for the interval 1951-2000 and assigned to each of the modern pollen assemblage. Pollen taxonomy has been harmonized, both in the calibration set samples and in the fossil records. The specific calibration set is the base for the second step, i.e. modeling the modern pollen-temperature relationship creating the transfer functions (or pollen-climate calibration models) by means of different numerical methods: the weighted-averaging (WA) regression and calibration (ter Braak and Barendregt, 1986; Juggins and Birks, 2012 and reference therein), the weighted-averaging partial least square regression and calibration (WAPLS) (ter Braak and Juggins, 1993) and the Modern Analogue Technique (e.g. Guiot,1990). The last step was the application of the transfer functions to the fossil pollen records to estimate the summer temperature values and the evaluation of the obtained reconstructions. Before applying the transfer functions (or pollen-climate models) to the fossil records, the statistical performances (root mean square error of prediction, RMSEP and r^2 between predicted and observed summer T values) were checked in cross-validation. The goodness of the calibration set in terms of availability of modern analogues for each fossil pollen sample was also evaluated using the diagnostics of the Modern Analogue Technique. The evaluation of past climate reconstructions, besides checking the diagnostics of the method used, was carried out using comparison with other climate proxy records (e.g. Juggins and Birks, 2012) and statistical significance test as suggested in Telford and Birks, 2011. When the pollen records covered the same interval of the instrumental period, a "real" validation of the models developed and of the obtained climate reconstructions were obtained by comparing the pollen-inferred temperature reconstructions with the instrumental data. The development of the pollen-climate models (or transfer functions), the evaluation of their performances and diagnostics, were carried out using R software (R Core Team, 2017) and the rioja, R package (Juggins, 2017).

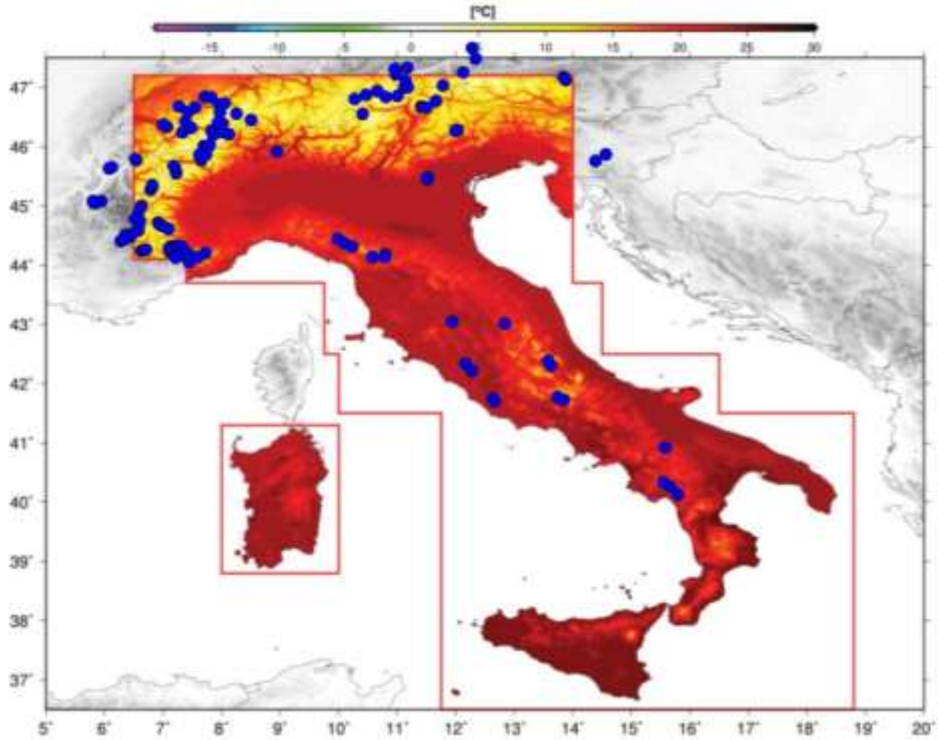

Figure 3: *Location of the 268 modern pollen samples (blue dots) forming the calibration set in use to obtain reconstructions in northern Italy plotted over the T july climatology (adapted from Brunetti et al., 2014).*

Evaluation of the pollen-climate calibration models and temperature reconstructions in northern Italy: comparison with instrumental temperature series

The pollen-climate models developed for past temperature reconstruction in northern Italy have been evaluated by comparing pollen-inferred temperature series with site-specific instrumental series in two records covering the last 200 years and provided with a pollen sample resolution of 5/9 years. The methodological approach and the possible influence of human activities in the pollen-inferred reconstructions were considered. The two study sites are located at different altitudes and are characterized by different mean climatological conditions. Lago Grande di Avigliana (LGA, 353 m asl) lies at the foothills of the western Alps: mean July temperature (reference period 1961-1990) is around 22°C. Lago di Lavarone (LAV, 1115 m asl) is located in the pre-alpine region: mean July temperature is around 16°C (Fig. 4, modified from Vallé et al. 2018). Sediment cores covering part of the Late Glacial and the whole Holocene were extracted from both lakes and studied for their pollen content to reconstruct the vegetation history, also including land-use changes in the two pollen source areas. Pollen records covering the last 200 years from Lago Grande di Avigliana and Lago di Lavarone are presented respectively in Finsinger et al. (2006) and in Arpenti and Filippi (2007). The sequence from Lago Grande di Avigliana has a good chronological control, based on varves counting, ^{210}Pb and ^{137}Cs dates: mean temporal resolution of the pollen record is ~4 years for the last 200 years. A good age control is available also for the Lago di Lavarone sequence: its pollen record has a mean sample resolution of ~9 years for the last 200 years with higher temporal resolution after ~1900 AD.

Site-specific monthly instrumental temperature series have been computed for Lago Grande di Avigliana (1833-2010) and Lago di Lavarone (1807-2010) with the methods presented in Brunetti et al. 2014, 2012, 2006. Summer temperatures have been calculated by averaging June, July, August monthly temperature values. To highlight the temperature trends and to facilitate the comparison and the correlation between the instrumental records and the pollen-inferred reconstructions, the instrumental summer temperature series were smoothed with loess regression (for LGA span=0.05, for LAV span=0.1) following the pollen resolution. PAST statistical software version 3.3 (Hammer et al., 2001) was used (Fig. 4, modified from Vallé et al. 2018).

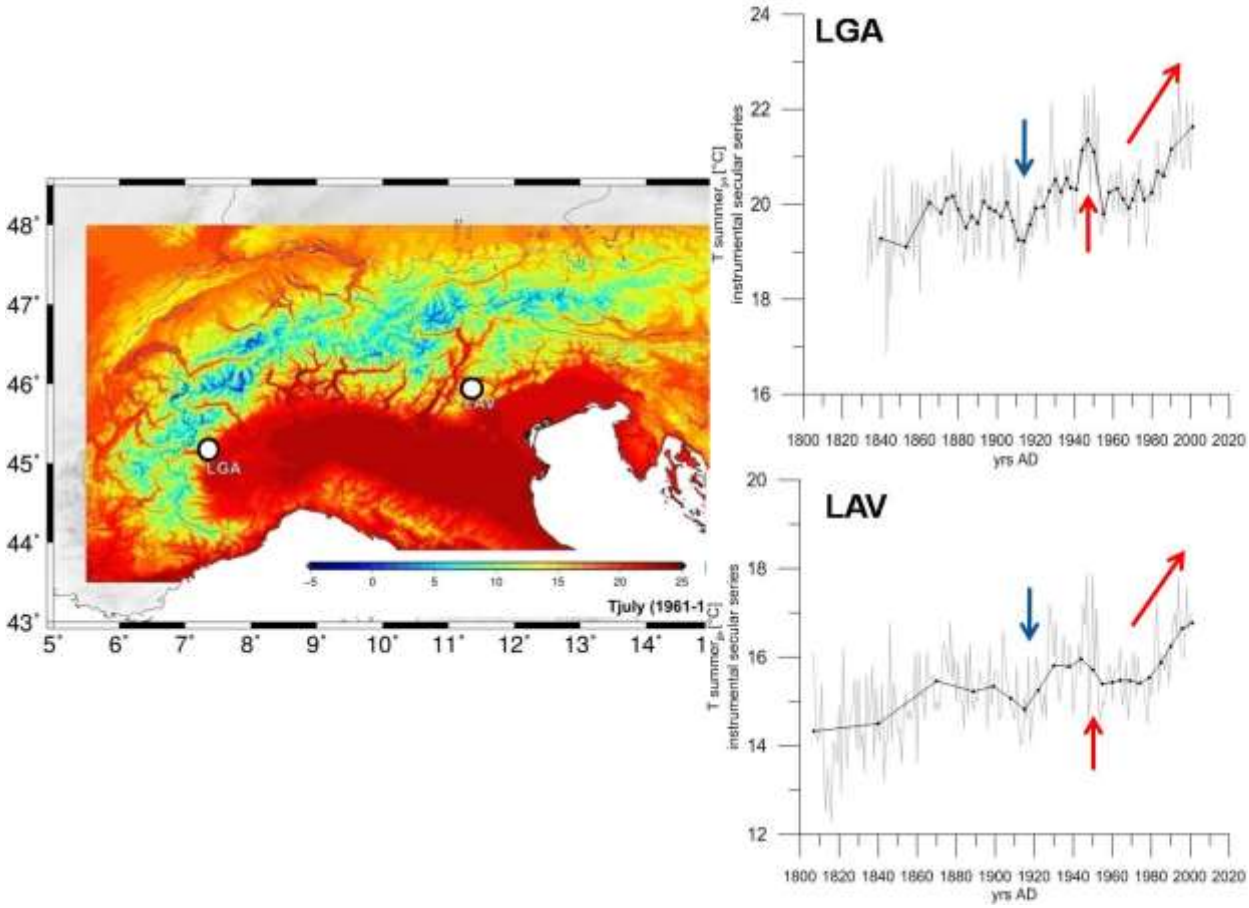

Figure 4. *Location of the study sites Lago Grande di Avigliana (LGA) and Lago di Lavarone (LAV). The instrumental summer temperature series computed for these study sites are also shown; the light grey lines represent the annual records and the dark thick lines represent the smoothed records corresponding to the pollen sample resolutions. The warm intervals and the cold interval recorded during the last 200 years are indicated respectively with red and blue arrows (modified from Vallé et al. 2018).*

Pollen-inferred summer temperature reconstructions obtained for Lago Grande di Avigliana and Lago di Lavarone are shown together with the instrumental series (Fig. 5). WA pollen-inferred summer temperature values obtained for LGA are almost constantly underestimated if compared to the instrumental series. They are instead slightly overestimated for LAV. Despite the shift in the absolute values at LGA, the decadal variability and the long-term trend in summer temperature instrumental series are also detectable in the pollen-inferred reconstructions, and this is true for both sites. Interestingly, the LGA pollen-inferred summer T reconstruction recognizes the warmer interval recorded between 1940 and 1950 AD. The direct comparison of the WA pollen-inferred summer temperatures with the instrumental series yielded a moderate correlation for LGA (R^2=0.41) and a good correlation for LAV (R^2=0.7).

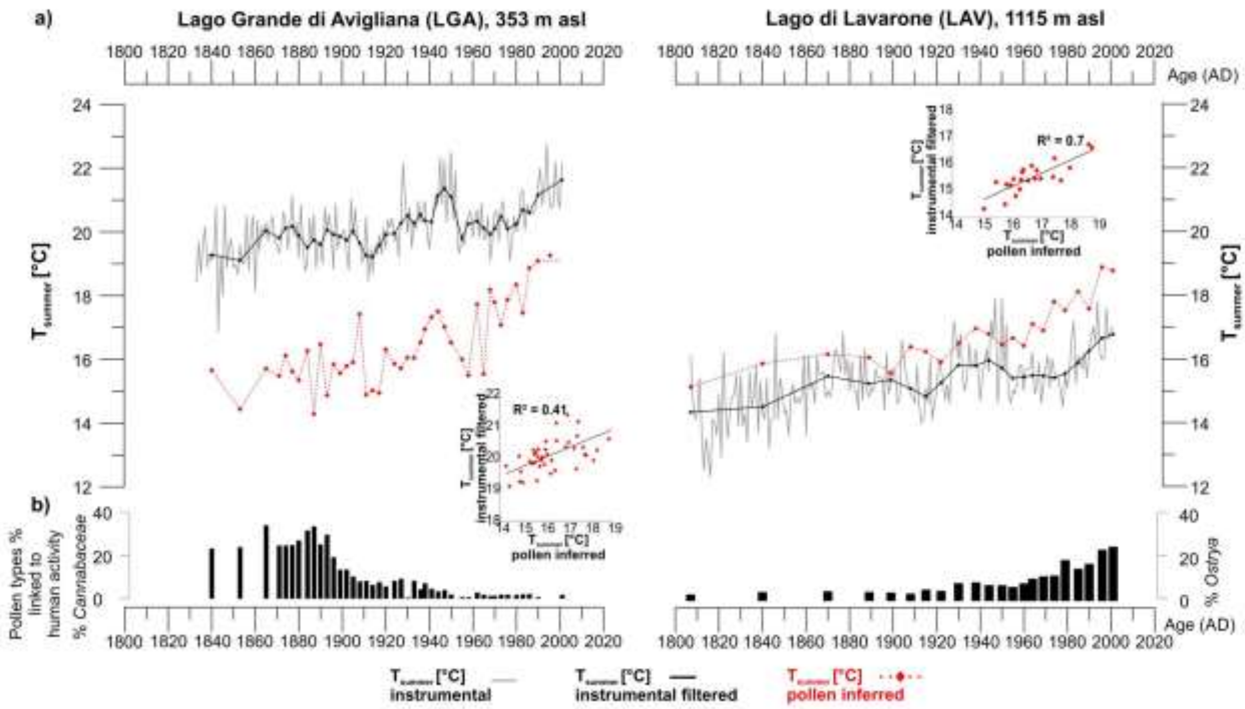

Figure 5. *a) Comparison between instrumental T summer series (grey curves) and the pollen-inferred T summer reconstructions (red dotted curves) obtained for LGA and LAV with the WA method. The instrumental summer T series were smoothed with loess regression (for LGA span=0.05, for LAV span=0.1) according to the pollen resolution (black curves). Coefficient of determination between the two series are also shown. b) Percentages of an anthropogenic pollen taxa, Cannabaceae from LGA and Ostrya from LAV, which might influence the pollen-inferred temperature reconstructions (from Vallé et al. 2018).*

During the last two centuries mean air temperature in Italy shows an increasing trend of 1°C per century with an intensification occurred in the last decades (Brunetti et al. 2006, 2013). Beside this century-long temperature increase, negative trends over shorter periods have been observed at the beginning of the 19th century and between 1950-1970 AD (Brunetti et al. 2006, 2013). Pollen-inferred summer temperature reconstructions capture the general warming of the last centuries. Fig. 5 also presents the pollen percentages of two important pollen-productors which were affected by human land use changes, i.e. Cannabaceae from the pollen record of Lago Grande di Avigliana (Finsinger et al., 2006) and *Ostrya* from the pollen record of Lago di Lavarone. Cannabis sativa was cultivated in northern Piedmont in the 19th century until ~1950 AD (Finsinger et al. 2006 and reference therein). Whether this taxon is included or not in the pollen sum used for the temperature reconstructions, it influences the reconstructed absolute values. This issue needs to be carefully considered because this pollen taxon is not well represented in the used calibration set. Concerning *Ostrya*, this species is today the main component of forest vegetation in the pollen source area of Lago di Lavarone. Its expansion started around 1965 AD, favoured by decreased human activities in the area (Arpenti and Filippi, 2007). We are aware that WA methods are able to solve the "non-analogues" problems but suffer from the "edge effects" (Juggins and Birks, 2012 and reference therein). Being Lago Grande di Avigliana summer temperature values at the end of the calibration set summer temperature gradient, the constant underestimation of the LGA pollen-inferred summer temperature might be due to this reason. This rigid shift in absolute values (which does not affect the long-term variability) is reduced by using WAPLS model (not shown in fig. 5).

Our results show that pollen records obtained from lacustrine sediment cores can be used to obtain pollen-inferred temperature reconstructions with trends comparable to instrumental data over the last 200 years, provided that: 1) pollen records have a robust age control and high sample resolution (ideally less than a decade), 2) proper calibration sets and adequate numerical techniques are used to develop pollen-climate models and transfer functions to be applied to fossil pollen records. The human activities and their effects in the pollen relative abundances must be considered and evaluated in the process of taxa selection before applying quantitative methods.

Reconstructions of precipitation from pollen data

The three step approach (Juggins and Birks, 2012) is valid also to reconstruct precipitation from pollen data. But the calibration set to be used must be designed to maximize the ecological sensitivity of pollen taxa for precipitation. Furthermore, the fossil pollen record must be located in an area where precipitation are the most important variable influencing the variance of pollen data. An attempt of Holocene precipitation reconstructions based on pollen data has been done using a fossil pollen record from a high-elevation site located in the oceanic external alpine chains of Lombardy (Furlanetto et al., 2018). The Holocene precipitation reconstruction was found statistically significant to the test proposed by Telford and Birks, 2011 and the inferred changes were in agreement with the fluctuations of lake levels (Furlanetto et al. 2018).

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