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ORIGINAL PAPER

An experimental 392-year documentary-based multi-proxy (vine and grain) reconstruction of May-July temperatures for Kőszeg, West-Hungary

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Abstract In this paper, we present a 392-year-long preliminary temperature reconstruction for western Hungary. The reconstructed series is based on five vine- and grain-related historical phenological series from the town of Kőszeg. We apply dendrochronological methods for both signal assessment of the phenological series and the resultant temperature reconstruction. As a proof of concept, the present reconstruction explains 57% of the temperature variance of May–July Budapest mean temperatures and is well verified with coefficient of efficiency values in excess of 0.45. The developed temperature reconstruction portrays warm conditions during the late seventeenth and early eighteenth centuries with a period of cooling until the coldest reconstructed period centred around 1815, which was followed by a period of warming until the 1860s. The phenological evidence analysed here represent an important data source from which non-biased estimates of past climate can be derived that may provide information at all possible time-scales.

Keywords Biophysical indicators · Climate reconstruction · Summer temperatures · Western Hungary

Introduction

Results and milestones of scientific research related to the connection between long-term, documentary-based, vine phenology information and temperature have recently been discussed by many authors (e.g. Brázdil et al. 2005, 2008; Menzel 2005; Meier et al. 2007; Rutishauser et al. 2007). Among the vine-related biophysical indicators, vine harvest dates have had most attention and have formed the basis of 400- to 500-year-long temperature reconstructions in France (e.g. Le Roy Ladurie 1971, Le Roy Ladurie and Baulant 1980; Bell 1980; Chuine et al. 2004; Menzel 2005), Switzerland (e.g. Pfister 1981, 1984; Burkhardt and Hense 1985; Meier et al. 2007), Germany and Austria (Glaser and Hagedorn 1991; Strömmer 2003; Maurer et al. 2009) and Italy (Mariani et al. 2009). In recent years, vine harvest date series have also been utilised in multi-proxy reconstructions—normally combined with other, natural proxy data sources such as tree-ring width and isotopic series, and ice-core oxygen isotope series (e.g. Guiot et al. 2005; Etien et al. 2008). Grape harvest dates have also been used to assess existing NAO reconstructions (Souriau and Yiou 2001). Other vine-related indicators, such as blossoming and beginning of grape ripening, as well as quality and quantity of harvested vine, have also been incorporated into long-term temperature reconstructions (e.g. Pfister 1981, 1984; Lauer and Frankenberg 1986; Strömmer 2003).

Information on grain harvests, such as dates and quantity, are often available from documentary sources, and have proved to be a sensitive indicator of late spring–early summer temperatures (see, e.g., Pfister 1979, 1984;

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Glaser and Hagedorn 1991; Brázdil et al. 2005). Based on rye harvest dates, a summer temperature reconstruction was developed from the 1740s for Estonia (Tarand and Nordli 2001), and for eastern England over the thirteenth–fifteenth and eighteenth–nineteenth centuries (Pribyl and Pfister 2009). Dates of payments for grain harvesting (wheat, rye, oat) in the early fifteenth–seventeenth centuries were analysed for north-west Bohemia and used for temperature reconstructions (Brázdil and Kotyza 2000). A 270-year temperature reconstruction based on the combination of rye harvest dates from farmer diaries and changes in terminal moraines of glaciers was prepared for western Norway (Nordli et al. 2003).

The advantage of such phenological series is that vine- and grain-related temperature reconstructions can act as an alternative to tree-ring-based reconstructions in low elevation areas where tree growth is more likely to be limited by moisture stress than temperature (e.g. Brázdil et al. 2002; Kern et al. 2009; Siklósy et al. 2009). The Kőszeg region of western Hungary, the study area in this paper, has special importance as there is a large amount of potential phenological information. Initial investigations in the early twentieth century identified the relationship between vine-sprout development and early spring temperatures (Berkes 1942). The series, based on the length of vinesprouts on 24 April every year, is available from 1740, and was used for a March–April temperature reconstruction (Střeštík and Verő 2000). Szövényi (1965) and Bendefy (1972) also discussed the relationship between summer temperature and the seventeenth—nineteenth century vine harvest dates, while Péczely (1982) identified a connection between May–September temperatures and wine quality and quantity indices in Kőszeg.

In this paper, a combination of biophysical indicators, related to vine and grain phenology, are analysed, and a preliminary multi-proxy reconstruction of May–July temperatures for 1618–1873, based on the combination of five individual series, is presented for the Kőszeg area. This is the first time that these series, based on original archival research of contemporary institutional sources of Kőszeg town, have been investigated in their entirety. The resultant reconstruction is important not only to provide a valuable comparison to more traditional tree-ring based reconstructions but they can also be widely utilised and provide important additional information for economic and social history research as well as for decision-makers in, for example, long-term risk-management calculations.

Materials and methods

Study area and data

Study area, data and rationale for study period

The town of Kőszeg (47°23'N, 16°32'E) and its small but well-defined historical wine region are located at the eastern-southeastern foothills of the Alps in western Hungary, 3 km from the border with Austria, at an elevation between 270 and 400 ma.s.l. (Fig. 1). Due to its semi-basin position, Kőszeg and its vineyards are mainly exposed to the south, east and southeast and open towards the inner

Fig. 1 Kőszeg study area in relation to Budapest and Vienna

parts of Hungary. The region is relatively protected from the west and northwest (Austria) by the Kőszeg Hills (alpine foothills) up to 880 m elevation.

The temperature reconstruction discussed herein is derived from five different phenology series: beginning of grape ripening dates (GR), beginning of vine harvest dates (VD), collection dates of vine tithes (TV), collection dates of grain tithes (TG) and vine quality (VQ) indices (Fig. 2; for more details concerning background, see Appendix 1). Grain tithe collection dates are directly connected to the timing of grain harvest. Compared to wine, grain production traditionally played a marginal role in the Kőszeg economy, but the series is still available from the early seventeenth to the mid-nineteenth century and has much relevance for the present study. Another important factor which must be emphasised is that the main vine and grain types, as well as the predominant management practices, did not change throughout the study period, so ensuring a homogenous consistent dataset (see Appendix 2).

Among the five series applied, the most continuous is VD, being available sporadically from 1630 and almost continuously from 1644 onwards (until 1944) with only a few years missing (Fig. 2). GR is available sporadically from 1618, is more continuous with gaps from 1630 and ends in 1873. TV can be found for the period 1708–1847 with some gaps, whereas TG are sporadically available from 1617 and are more continuous, but still have gaps from 1650 to 1847. The VQ series starts in 1740 and is almost continuous until the present day. However, only the section before the mid-1870s was applied in this investigation. The combined

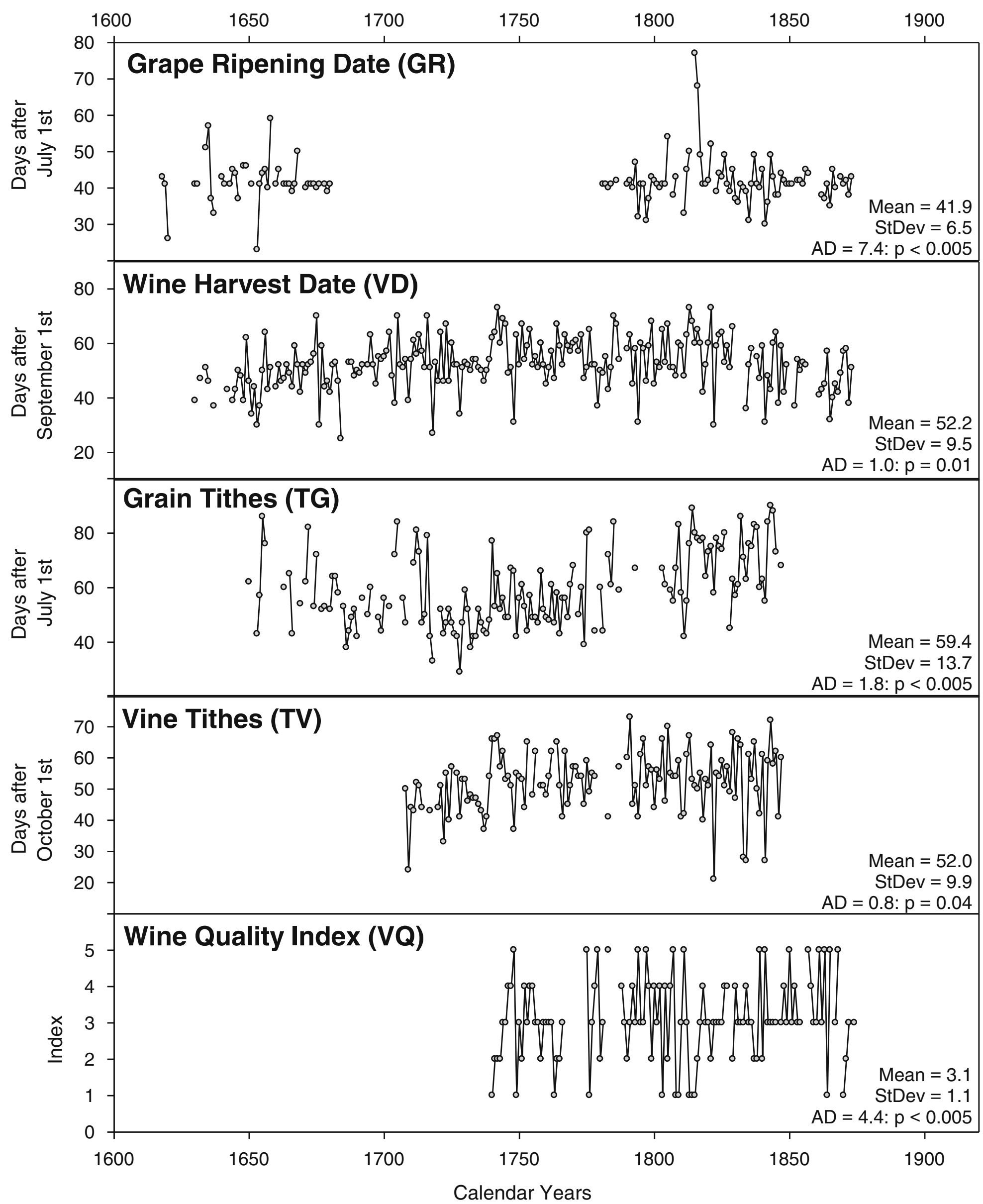

Fig. 2 Raw phenological series. *AD* Anderson–Darling test for normality (Anderson and Darling 1952)

five series have, at present, missing dates for 1621–1625, 1627–1629, 1633, 1638–1639 and 1693.

1873 is defined as the last year of the proxy data used in the present analysis. Although vine harvest dates, quality and other parameters were still documented in the local newspaper and the *Book of Vinesprouts* (n.d.), after the mid-1870s there is a rapid decrease in correlation between measured temperature and these biophysical indicators. The reasons of this change are predominantly due to the basic and irreversible changes of vine types, cultivation practices and the occurrence of diseases (see, e.g., Bariska 2001). Another reason was that the major train line, built in the area in the 1860s, avoided Kőszeg, and thus transportation possibilities greatly decreased compared to other vine regions (Szövényi 1966–1970) which ultimately led to a decline in wine production (Szövényi 1965). Additionally, during the 1870–1880 period, cold mid-autumn weather, early rotting and destruction by mice further affected the starting dates of grape harvest as well as quality of the wine (KTCD 1870-1880). Changes in ownership patterns (small-holders took over the lead) also occurred in the last decades of the nineteenth century. The town lost its vineyard properties and later the cooperative and the hill-community could not preserve the old traditions for regulation of the vine harvest and other dates of former importance. Due to these reasons, a gradual shift from quality- to quantity-based wine production occurred from the last decades of the nineteenth century onwards. Moreover, fundamental changes in vine types occurred, which among others was documented in the *Book of Vinesprouts* (n.d.), and thus vine harvests started earlier and earlier (see Appendix 2). The appearance of the phylloxera disease in the Kőszeg area was officially stated only in 1899. After the phylloxera infection, vinestocks were not replanted, and thus the area of vineyards decreased to half by the 1910s (Bariska 2001).

Methods

In the following analyses, we follow modified dendrochronological methods for both signal assessment of the phenological series and the resultant temperature reconstruction. A similar approach was utilised by Leijonhufvud et al. (2008, 2010) for their Stockholm winter temperature reconstruction derived using port administrative records.

For all analyses henceforth, the sign of the GR, VD, TG and TV series (Fig. 2) were inverted so that they are positively correlated with each other and MJJ temperatures (see later). Table 1 shows Spearman's correlation values between each of the proxy records. The Spearman's correlation was used as the series are not normally distributed (Fig. 2) and the VQ data are an ordinal index. The implications of the skewed nature of the data are discussed later with respect to rationalising the need for using a series mean composite for the final reconstruction. Overall, there is a highly significant common signal between the different series. The strongest relationship is between VD and TV (r=0.63) and weakest between TG and VQ (r = 0.21, p=0.09). The mean inter-series correlation (RBAR) between all possible bivariate pairs is 0.45. In dendrochronology, the RBAR is used as a measure of common signal between tree-ring series and can be utilised to assess the signal strength of a mean composite series derived from averaging several records together. Herein we assess the signal strength using the Expressed Population Signal statistic (EPS) (Wigley et al. 1984; Briffa and Jones 1990) which quantifies the theoretical correlation of a composite mean time-series with the theoretical infinitely replicated population signal. The following equation uses the RBAR value to calculate the EPS value:

$$EPS = \frac{n^*\bar{r}}{n^*\bar{r} + (1 - \bar{r})}$$

where n is the number of proxy series used and $\bar{r}$ is the RBAR. A commonly accepted threshold of acceptance in dendroclimatology is 0.85 (Wigley et al. 1984). The EPS value for the current five series dataset is 0.80 which is only slightly below this threshold. The above equation can be re-arranged to estimate the minimum number of proxies series (n) needed to obtain an EPS of a particular value:

$$n = \frac{(\bar{r} - 1)\, EPS(x)}{\bar{r}\, (EPS(x) - 1)}$$

Table 1 Correlation (Spearman's) matrix between the five phenological series

Series	Correlations	VD	TG	TV	VQ
GR	*r*	0.47	0.48	0.40	0.53
	p value	0.00	0.00	0.00	0.00
	df	91	39	51	64
VD	*r*		0.34	0.63	0.63
	p value		0.00	0.00	0.00
	df		115	113	98
TG	*r*			0.34	0.21
	p value			0.00	0.09
	df			92	67
TV	*r*				0.45
	p value				0.00
	df				82

For these analyses, only consecutive value of 3 observations or more were used and single or double values were excluded

GR beginning of grape ripening dates, *VD* beginning of vine harvest dates, *TG* collection dates of grain tithes, *TV* collection dates of vine tithes, *VQ* vine quality where the threshold value of EPS (x) is user defined (in this case 0.85) and $\bar{r}$ is the mean between series correlation. Again, using the RBAR value of 0.45, the theoretical number of series needed to acquire a robust mean composite series is seven.

Correlation analysis between each of the phenological series and monthly mean temperatures from Budapest, climatologically considered as the nearest meteorological station to the study area (as also emphasised with comparisons in previous studies: see, e.g., Berkes 1942; Střeštík and Verő 2000), was made to ascertain the seasonal response of these data (Fig. 3). The dominant common response is with May–July temperatures although some coherence is observed for the TV and VQ series against September and October temperatures. Overall, the common response of these five series to a similar climatic parameter is not surprising as they show a degree of common variation (Table 1). Therefore, for this study, because of the shared common signal, we used these data to reconstruct Budapest May-July mean temperatures.

Each of the individual phenological series (Fig. 2) can be viewed as having a common signal—their relationship with MJJ temperatures—and independent noise characteristics. Therefore, in a similar way that dendrochronologists average a number of trees together to derive a mean composite site series, herein we composite the five phenological series to derive a mean series that will be calibrated against mean MJJ temperatures. This compositing will minimise the independent noise characteristics of the individual series, while enhancing the common signal. As the series are on different scales (dates vs indices), they were first standardised to z-scores (zero mean and unit standard deviation) relative to the 1780–1847 most replicated period (Fig. 4a, b). These transformed series were then averaged together. Following similar procedures detailed in Leijonhufvud et al. (2008, 2010), to minimise

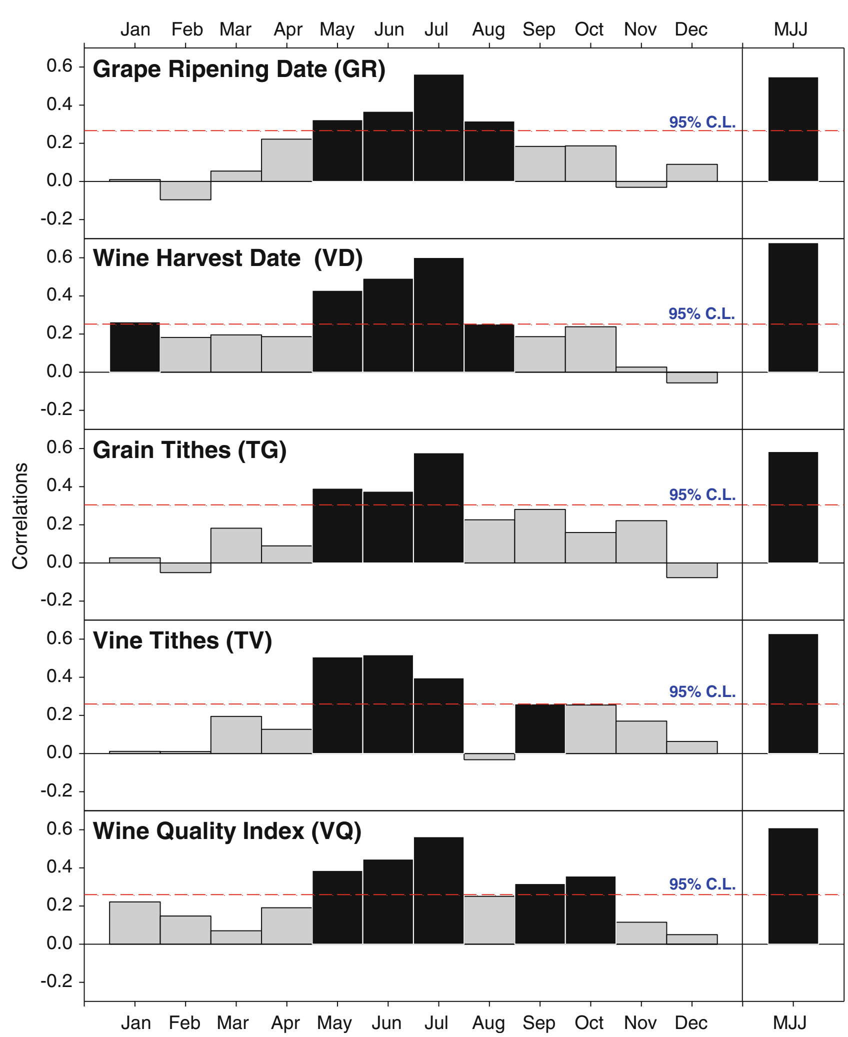

Fig. 3 Correlation response function analysis (1780–1847) between the phenological series and monthly mean temperatures from Budapest (Böhm et al. 2009). Note: the sign of the GR, VD, TG and TV series have been inverted to show all correlations as positive

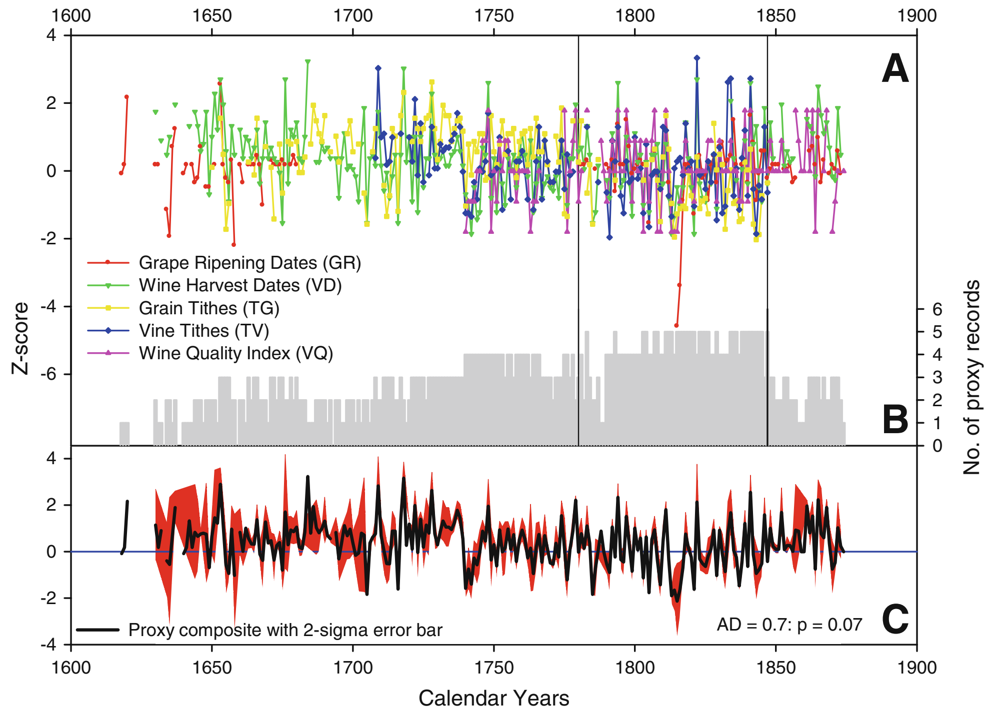

Fig. 4 **a** Individual phenological series standardised to z-scores with respect to the 1780–1847 period; **b** proxy series replication; **c** mean composite series with 2-sigma error bars

variance artefacts due to the changing number of observations through time (see Fig. 4b), the variance of the final mean composite series was adjusted using the following equation (Osborn et al. 1997):

$$Y(t) = X(t)\sqrt{\frac{n(t)}{1 + (n(t) - 1)\bar{r}}}$$

where *X(t)* is the simple mean value at time *t*, *n (t)* is the number of series at time *t*, $\bar{r}$ is the RBAR, and *Y(t)* is the adjusted mean value at time *t*. The final adjusted composite mean series is presented in Fig. 4c. Unlike the raw phenological series (Fig. 2), this composite record is normally distributed when examined using the Anderson and Darling (1952) test and can therefore be used as a predictor variable for ordinary least square regression-based calibration.

The correlation response function analysis (Fig. 3) identified that the optimal season to reconstruct using these data is May–July mean temperatures. A traditional split period calibration and verification method was employed. As the climate data start in 1780 and the composite proxy mean series ends in 1873, this period was divided into two equal periods. Calibration was independently made on both the 1780–1826 and 1827–1873 periods while the verification undertaken on the periods not included in calibration (1827–1873 and 1780–1826). Verification was undertaken using the square of the Pearson's correlation coefficient (r^2), the reduction of error (RE) and the coefficient of efficiency (CE). The regression residuals were assessed for potential biases at decadal time-scales using the Durbin–Watson statistic for autocorrelation and multi-decadal to longer term time-scales by testing for linear trends.

The RE statistic tests whether a reconstruction provides a better estimate of climatic variability than simply using the mean climatology in the calibration period (Cook and Kairiukstis 1990; Cook et al. 1994). It is calculated as:

$$RE = 1.0 - \left[\frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x}_c)^2}\right]$$

where x_i and $\hat{x}_i$ are the actual and estimated data in year *i* of the verification period, and $\bar{x}_c$ is the mean of the actual data in the calibration period. The value of RE can range from negative infinity to a maximum value of 1.0 which indicates perfect estimation. If the total difference between the estimates and the actual data is less than the total difference between the calibration mean and the actual data, the RE statistic will be positive.

The CE statistic is similar to RE except that its benchmark for determining model skill is the verification period and not the calibration period (i.e. the difference between RE and CE is in the denominator term). It can be described as an expression of the true r^2 of a regression equation when applied to new data (Cook and Kairiukstis 1990; Cook et al. 1994). The equation used to calculate CE is expressed as:

$$CE = 1.0 - \left[\frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x}_v)^2}\right]$$

where $\bar{x}_v$ is the mean of the actual data in the verification period. Like RE, CE can range from negative infinity to a maximum value of 1.0 which indicates perfect estimation. Again a positive value signifies that the regression model has some skill. When $\bar{x}_v = \bar{x}_c$, CE=RE. When $\bar{x}_v \neq \bar{x}_c$, RE will be greater than CE by a factor related to the difference in means. In comparison to RE, CE is more difficult to pass, and is therefore a more rigorous verification statistic.

Results and discussion

Figure 5 shows the calibration/verification results against Budapest temperatures. It should be noted that we utilise the recently homogenised series where warm season biases prior to the late nineteenth century have been adjusted to account for insufficient sheltering from direct sunlight (Böhm et al. 2009). For both the early (1780–1826) and late (1827–1873) periods, the proxy composite explains >50–60% of the temperature variance. Verification is robust with RE and CE values for both periods being>0.40–0.50.

The explained variance over the full period is 57% with the residuals showing no significant autocorrelation (DW= 1.76). However, the residuals portray a slight but significant (95% CL) negative linear trend, indicating that the current proxy data composite may either not be picking up all the long-term trend in the instrumental data or that the early instrumental data are still “too warm” (Böhm et al. 2009).

Herein, we have developed an exploratory reconstruction of May–July mean temperatures using five phenological series for the Kőszeg region in Hungary. Despite the relatively sparse nature of the input data series and the fact that the individual series have a variety of statistical problems related to their non-normal properties. Averaging them, together after appropriate normalisation and variance stabilisation, results in a normally distributed mean composite series that calibrates and verifies very well with Budapest May–July temperatures (Fig. 5). However, despite these very strong results, a final important step for reconstruction validation is to compare such data with comparable independent data. Figure 6 compares the Kőszeg reconstruction (hereafter KOS) to other independent proxy

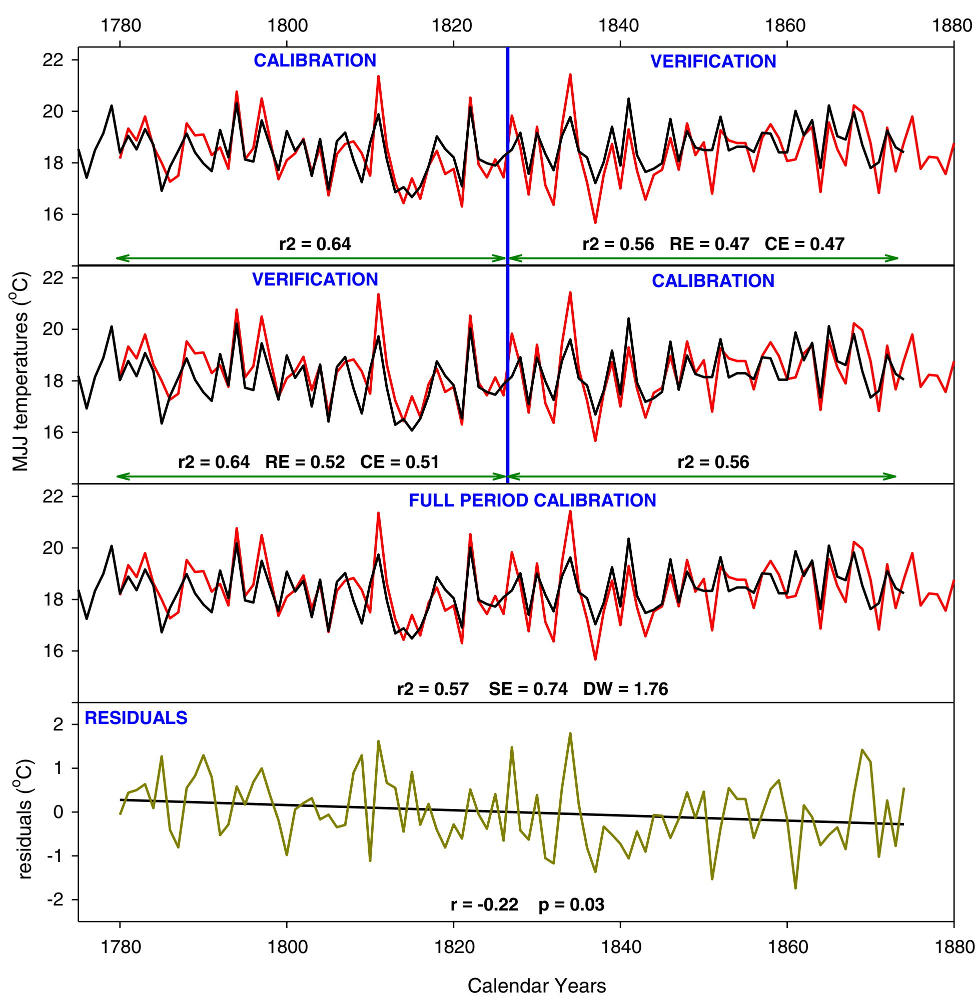

Fig. 5 Calibration and verification results of the phenology composite with May–July Budapest mean temperatures. Reconstruction *black*; instrumental data *red*

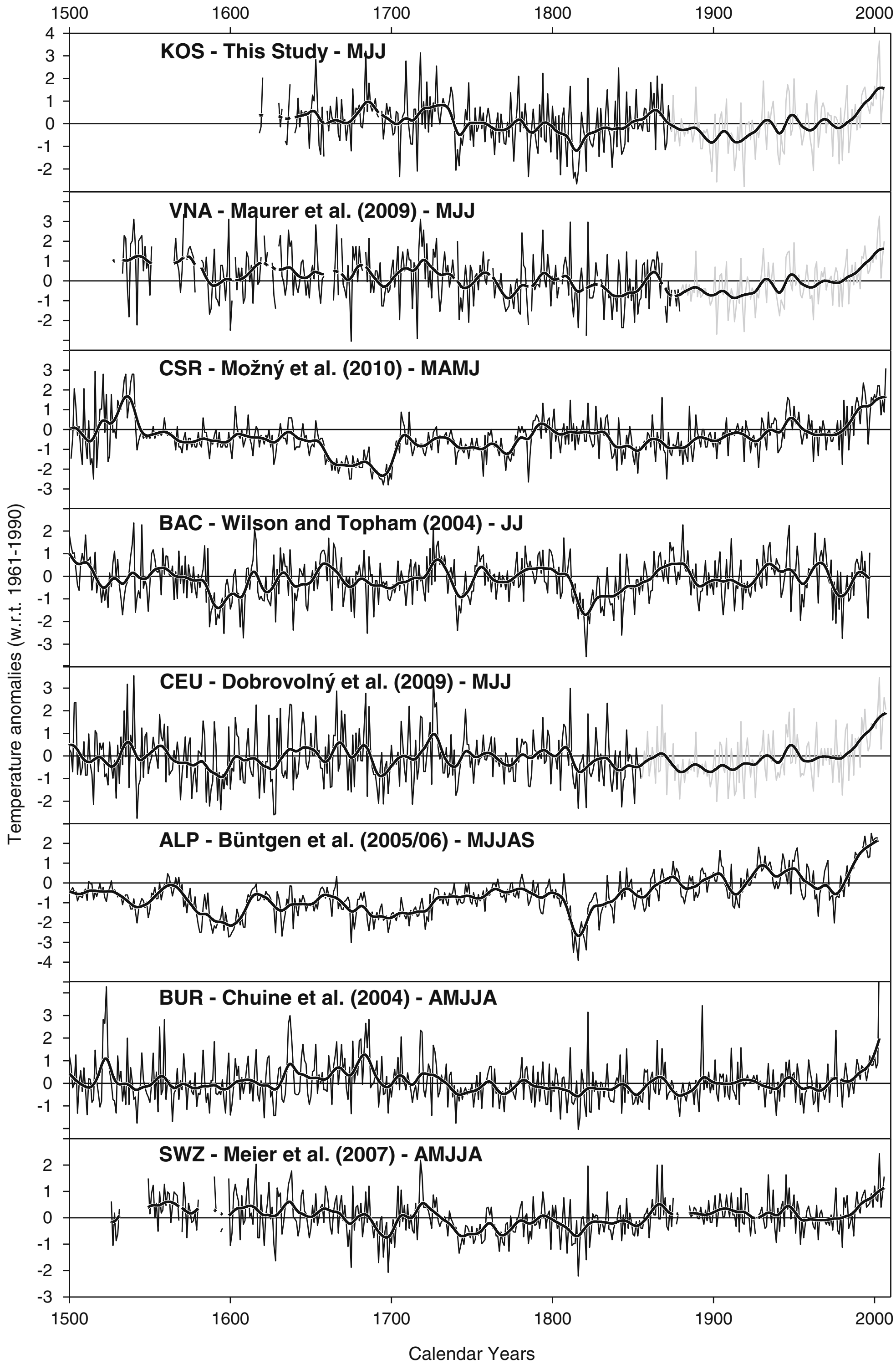

Fig. 6 Comparison of the Kőszeg (KOS) reconstruction to other summer temperature reconstructions from around Europe. All time series have been transformed to temperature anomalies with respect to 1961–1990. The data after 1874 (KOS) and 1855 (CEU) are represented by instrumental data (in *grey*). Before the historical series were spliced to the instrumental data, the historical data were transformed to have the same mean and standard deviation as the instrumental data over the period of overlap. This ensures that there is no reduction in variance in the final spliced series due to the regression based calibration of the historical data. The thick line represents a 20-year Gaussian smoothing function

based spring/summer temperature reconstructions from around Central Europe:

- VNA is a recently developed May–July mean temperature reconstruction for the Vienna region using grape harvest data (Maurer et al. 2009). This series explains 62% of the Vienna instrumental data and provides an invaluable independent proxy from a neighbouring region for comparison.
- CSR is a similarly derived reconstruction to this study using winter wheat harvest dates of wheat, rye, barley and oats from the Czech Republic (Možný et al. 2010).

The composite of these series calibrates with an r^2 of 0.70 and is well verified against March–June mean temperatures.

- BAC is a tree ring-width based proxy record compiled using living and historic series from the Bavarian Forest and Austrian Alps region (Wilson and Topham 2004). This highly replicated Spruce ring-width chronology correlates best with June–July temperatures (r^2=0.20) but shows little long term secular scale information as the tree-ring data were not processed to capture long term variability. This series is most robust at decadal and multi-decadal frequencies only.
- CEU represents the documentary data-based Central European reconstruction of Dobrovolný et al. (2010) which utilises historical indices from the Czech Lands, Germany and Switzerland to derive monthly estimates of past temperatures back to AD 1500. Herein, we compare to the mean of the May–July reconstructed temperatures which explain ~67% of the temperature variance. The period after 1855 is represented by instrumental data of 11 Central European stations.
- ALP as a fusion of two tree-ring summer temperature reconstructions (Büntgen et al. 2005, 2006) which was compiled for a large-scale hemispheric analysis (Wilson et al. 2007). The 2005 ring width and 2006 maximum density based summer reconstructions were averaged together after they had been normalized to their common period. This combined composite series calibrates (r^2=0.41) optimally with May–September temperatures (Wilson et al. 2007).
- BUR is a reconstruction of April–August temperatures for the Burgundy region derived from grape harvest dates using a process-based phenology model developed for the Pinot Noir grape and explains 56% of Paris mean April–August temperatures (Chuine et al. 2004).
- SWZ represents a similar reconstruction of April–August temperatures derived from grape harvest dates for Switzerland (Meier et al. 2007). This series explains 57% of the temperature variance when calibrated.

KOS portrays warm temperatures during the late seventeenth and early eighteenth centuries with a period of cooling until the coldest reconstructed period centred around 1815 (the coldest reconstructed year). There is then a period of warming until the 1860s, cooling until the early twentieth century and then warming through the twentieth century with maximal warming in the last few decades.

Table 2 presents a correlation matrix (1618–1855) between the reconstructions shown in Fig. 6. As expected, a strong correlation (r=0.63) is noted between KOS and VNA as they are derived from similar proxy types and their target regions are closely located. Despite the considerable distance to Burgundy (~900 km) and Switzerland (~600 km), KOS correlates very well with the BUR and SWZ series (>0.5). The strongest correlation (r=0.78) is found between BUR and SWZ. The correlations with the tree-ring-based BAC and ALP summer temperature reconstructions are, however, not particularly high (r=0.29 and 0.19). The correlation of 0.52 between KOS and CEU is very encouraging, however, as these two reconstructions are independently derived and therefore provide good mutual validation of both these records. However, KOS does not compare so favourably with CSR which presumably reflects the difference in the seasons that both series portray (MJJ vs MAMJ). Overall, these variable correlation results likely portray that similar proxy types (i.e. grape harvest dates) respond to similar environmental conditions and therefore correlate well with each other, but the general simple linear interpretation that is often made between proxy records and temperatures is likely a simplification of a much more complicated relationship. However, the highly significant correlation between KOS, VNA, CEU, BUR and SWZ, plus the strong calibration/verification results (Fig. 5) imply that the KOS data likely represent a robust dataset for reconstructing past MJJ temperatures.

Some key features appear to be coherent between the reconstructions presented in Fig. 6. All the series show warming from the nineteenth century to the present with a particular marked increase in recent decades. BAC does not show these trends so clearly which likely reflects the individual (data-adaptive) tree-ring series detrending methods used which would potentially remove such long-term trends (Cook Edward et al. 1995). Although weakly defined in VNA, CEU, BUR and SWZ, and non-existent in CSR, there is a generally consistent cool phase between ~1810 and 1825 which coincides with a period of low solar irradiance (the Dalton minimum; Stuiver 1961; Bard et al. 2000; Bond et al. 2001; Robertson et al. 2001) and high volcanic activity (e.g. Tambora, April 1815; Newhall and Self 1982; Briffa et al. 1998; Robertson et al. 2001; Písek

Table 2 Correlation matrix between the independent proxy-based summer temperature reconstructions (Fig. 5)

	VNA	CSR	BAC	CEU	ALP	BUR	SWZ
KOS	0.63	0.17	0.29	0.52	0.19	0.51	0.53
VNA		0.32	0.35	0.59	0.17	0.57	0.63
CSR			0.11[a]	0.41	0.17	0.23	0.39
BAC				0.48	0.44	0.32	0.37
CEU					0.37	0.69	0.66
ALP						0.23	0.33
BUR							0.78

Analysis calculated over the 1618–1855 period represented only by proxy data

[a] Correlation not significant at 95% CL

and Brázdil 2006). It is interesting to note, however, that despite 1815 being the coldest reconstructed year in the KOS series, it is 1816 (the so-called "year without a summer") that is consistently the coldest reconstructed year in the nineteenth century for the VNA, CEU, ALP, BUR and SWZ records. The 1815 cold year in KOS is partly driven by the extreme value (−4.6 Stdev) for this year in the GR data (Fig. 4a). It should be noted, however, that there is no significant residual deviation when these data are calibrated (Fig. 5) so there appears no significant bias when including this outlier value. Overall, the fact that this early nineteenth century cold phase is not seen in CSR, and is only weak in VNA, CEU, BUR and SWZ likely reflects that this cool phase occurred in the post-May summer months for the few years after 1815 and was likely not a spring phenomenon.

Except for the CSR and ALP series, there is general evidence for warmer than average conditions between the ~1640s and 1740s with perhaps some evidence for a cooler pulse around the 1690s in CEU and SWZ as well as CSR and ALP. This latter period is often reconstructed as cool in many proxy reconstructions around the northern hemisphere and is likely that this period reflects short-term volcanic forcing superimposed on a period of low solar activity (the end of the Maunder Minimum) when global temperatures were generally cooler (Bard et al. 2000; Robertson et al. 2001; Shindell et al. 2001). Luterbacher et al. (2000) state that the cooling during this period in Europe is noted more in the winter, and the fact that it is so notable in CSR may reflect that the reconstructed season for this proxy includes the end of winter.

It is becoming more and more apparent that one of the key difficulties in palaeoclimatology is the robust modelling of lower frequency (multi-decadal to longer) long-term trends (Esper et al. 2004, 2005). Tree-rings, for example, can be biased in the low frequency domain as it is difficult to capture trends beyond the mean length of the samples in a dataset (Cook Edward et al. 1995). In a similar way, it is also very likely that there is a bias to decadal and higher frequencies when only using historical indices (Dobrovolný et al. 2010). Büntgen et al. (2005, 2006) processed their tree-ring data (ALP) with the so-called "Regional Curve Standardisation" method (Briffa et al. 1996; Esper et al. 2003) which potentially can capture longer term information. In fact, from Fig. 6, the ALP series clearly portrays much lower frequency variability than the other records. The ring width data used in the BAC series, however, were not processed using such methods and there is clearly very little centennial variability in the resultant record.

Wilson et al. (2005) advised caution when comparing different proxy based regional reconstructions from around the Greater Alpine Region due to observed differences between series. It is often not clear whether observed differences represent (1) real spatial differences in trends of climate variability, (2) varying seasonal windows portrayed by the differing proxy types, (3) differences in the methods used to process them, or (4) variance reflecting non-climatic noise. Figure 6 is a good case in point, and the observed differences must be interpreted in conjunction with known limitations of each proxy type.

Conclusions

In this paper, by applying dendroclimatological methods on multiple phenological observations, we have developed an almost 400-year-long May–July temperature reconstruction, based on vine- and grain-related biophysical indicators. As a preliminary proof of concept analysis, the present reconstruction explains 57% of the temperature variance of May–July Budapest temperatures. Comparison of this preliminary reconstruction with independent summer temperature reconstructions around Europe shows both common interannual and decadal to multi-decadal variance. There is, however, little agreement at the lower, red end of the frequency spectrum, and one of the challenges of palaeoclimatology is to capture past climate variability at all time-scales. Limitations of historical indices to reconstruct low frequency information are well known (Dobrovolný et al. 2010), and ongoing difficulties in extracting low frequency information from tree-ring data (Cook Edward et al. 1995; Briffa and Melvin 2010) is still an issue of debate. We believe that the phenological data presented herein represent an exciting data source from which non-biased estimates of past climate can be derived that theoretically could provide information at all possible time-scales. Our preliminary results represent a proof of concept analysis. Data collection is an ongoing process and more data that are currently being compiled will allow a marked improvement on the current analysis. The EPS signal strength analysis indicated that a minimum of seven phenological series would be required to derive a robust mean composite record. Further data collection will not only allow an extension of the reconstruction back in time but the inclusion of more data series, along with utilising the "evolutive" methods first described in Leijonhufvud et al. (2010), should allow both improvement in signal strength as well as the robust reconstruction of low frequency trends of past summer temperatures for the Kőszeg region of Hungary.

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Appendix: background information

Main characteristics of the phenology data series

Information, collected mainly from the Town Council Protocols of Kőszeg, on the beginning of vine harvest and election day of vine shepherds, and the beginning of grape ripening, is available sporadically from the late sixteenth century, and more continuously from the late 1610s onwards. Dates of collecting and summarising wine and grain tithes were derived from tithe accounts which were similarly kept in the town archives of Kőszeg. These data are sporadically available in documented form from the late sixteeenth century, and, due to the fact that Catholic church gave up its feudal rights and thus, this form of taxation ceased to exist in Hungary from 1848 onwards, are more continous from the late 1610s until 1847. In the case of all four series, each value was calculated from Calendar dates. Quality indices (1–5) were extracted from the descriptive data collected in the Kőszeg *Book of Vinesprouts* (n.d.) from 1740 onwards, although sporadic information is available for more than a century before.

Beginning of grape ripening: nomination and oath of vine shepherds

The so-called vine shepherds, nominated by the actual hill-masters, were elected in each year around the day of Saint Laurence (10 August) by the town council. Moreover, Saint Laurence' day was one of the dates when prediction/forecast was made about the wine quality and quantity of the forthcoming harvest (Bél 1984). The election or nomination of vine shepherds was mentioned in the town council protocols sporadically from the 1580s and more continuously from the late 1610s onwards with only few years missing. Vine shepherds were chosen and paid only from the days when soft grapes were already found and reported back to the town council (by hill-masters) in the vineyards. While this is essentially true before the late 1680s and after the 1780s, the date of shepherd-nominations (starting day of their contract) was predominantly fixed to 10 August regardless of the maturity of grapes between the late 1680s and late 1780s, even if short reports on stage of ripening were provided instead. Although, similarly to other series, other circumstances, such as disease, rainy weather, human factors etc. sometimes could also have some effect on this date (e.g. 1675: election on time, but very late grain and vine harvests), it is still one of the best indicators of actual early summer temperature conditions (see "Results and discussion").

The master series: beginning of grapevine harvest

As indicated in the Introduction, the beginning of grape harvesting is one of the most common biophysical indicators applied in phenology-based temperature reconstructions. Similar to the election of vine shepherds, the beginning of the vine harvest was discussed in the town council usually at least some days before the event, but the final decision was made by the mayor and a broader council of 24 elected men (see KTCP, Szövényi 1966-1970). Except for a few years, dates of vine harvest are almost continuously available in the town council protocols from the late 1610s onwards. Possible reasons for the gaps are related to (1) the document (actual entire volume) being missing (e.g. KTCP 1693) or (2) extreme years when ripening was either very early (e.g. KTCP 1728, 1729), late (KTCP 1715, 1721) or did not occur at all due to poor weather conditions (i.e. very cold/wet conditions). Although vine harvest date series show a strong correlation with May–July temperature (Fig. 3), for single years, the beginning of grape harvest can in some cases also be influenced by other factors. The influences of these factors are usually minimal however (see Appendix Table 3, and details below). Due to the detailed descriptions of the decision-making process concerning the starting date of annual harvests, in many cases, it is possible to provide information about the influencing factors other than May–July temperature, and therefore provide additional uncertainties for certain years (see Appendix Table 3).

Among other influencing natural factors, September–October weather conditions (temperature, precipitation, frost and hail) might have some additional impact in determining the first day of harvest. However these impacts usually only affect the starting dates by 2–3 days (Appendix Table 3). Nevertheless, even in cases of unfavourable (social, economic) conditions, the council did not necessarily provide permission for an earlier harvest: good/normal quality received priority over quantity (e.g. KTCP 1722, 1725). Other natural reasons, only in exceptional cases, had an impact which resulted an alteration of the 'real' starting date by more than 2–3 days. Among human and economic influencing factors, the delay of harvest because of sunny autumn weather, for gaining higher quality but risking actual quantity, was probably important due to the fact that the

Table 3 Factors affecting vine harvest dates reported

Influencing factor	Way of influence	Harvest date	Estimated error	Reported cases	Years
Primarily weather-related	Exceptionally bad (cool) late winter–spring–summer	Grapes do not ripen at all (low sugar content), combined with bad early autumn weather	Does (can)not show magnitude of extreme	Great (weeks)	1740
	Harmful frost in spring	Much latter grape ripening	Late and bad	7 days or more	1713 (Bél 1984)
	Autumn rains, wet–cold weather before harvest	Affects sugar content and wine quality and quantity	Earlier	Max. 2–3 days (1666: 7 days; 1684: undefined)	1666, 1737, 1748, 1751, 1864, 1866, 1870, 1872
	Fast/great rotting started (often combined with rains)	Affects wine quantity and quality	Earlier	2–3 days	1653, 1673, 1684, 1689, 1722, 1738, 1769, 1774, 1778–1779, 1836, 1863
	Cooler May–July, warmer August–mid-October / or opposite	Less effective in detecting May–July temperature	Earlier or later	Undefined	1635, 1644, 1648, 1650, 1657, 1754
	Frost and snowin harvest time	No harvest can be started on the planned day	Later, when frost, snow released	6–7 days	1708
	Great hail or other great damage	Grapes and vinestocks perished	Earlier or no harvest	Max. 3 days (if there is a harvest)	1584?, 1696–1697, 1709, 1722, 1763
Other natural	Animal invasions: wasps, birds, mice	Seriously affects quantity	Earlier	Max. 3 days	1689, 1715, 1745, 1750, 1822, 1863
	New moon after full moon (also mentioned by Bél 1984)	No harvest allowed on the day of full moon, new moon and the following day	Later	2–3 days	1741–44, 1756
	Undefined	Harvest cannot wait without significant damages	Earlier	Max. 3 days	1704, 1730
Social/economic	Day of Saint Orsolya/ Ursula (country fair)	No harvest starts on the day and before	Later	1–2 days	1726–1727, 1677, 1777–1778, 1819, 1835, 1849, 1856
	Quality-production	Sunny late September–October weather may rise sugar content	Later (even if ripening is normal)	Few days	1738, 1742, 1749
	Road preparation, late tax payment	Road preparation of vine hills starts too late	Later	1–2 days	1715, 1757
	Church regulations: days of feast	No heavy works on Sunday and feast days	Later	1–2 days	1713, 1744
	War, disease, contradictions	Do not even wait for ripening / or harvest kept in secret	Earlier/later	2–3 days	1704, 1705, 1761

. Source: KTCP, Bél 1984, *Book of Vinesprouts* (n.d.)

town primarily lived on wine production and wine export and thus, quality was at least as important as quantity.

Moreover, no harvest started on the day (and preceding 1–2 days) of the country Fair of Kőszeg (Saint Orsolya's day), namely on 21 October or 1–2 days before (see, e.g., Szövényi 1966–1970). This rule lost its importance after the 1870s (e.g. vintage on 20–21 October: 1873, 1877, 1879). In general, society proved strongly flexible. A good example of flexible social reaction is that when the harvest was in danger (e.g. bad weather, birds, wasps, etc.), the church allowed Sunday/feast work in order to avoid any delay. Even in the case of the most severe non-climatic situations, for example war and plague, the town council seemingly managed to find the way (paying soldiers for protection, hiring people from the countryside for work) to ensure the correct timing of the harvest with respect to the ripening of the vines (KTCP: e.g. 1709, 1710). Only one case is known from the town council protocols (KTCP: 1705) when, besides early ripening, the beginning of harvesting was allowed earlier (only in really exceptional cases), clearly to stop a sudden decrease of harvested grapes, caused by war and surrounding armies.

Consequently, although human factors should also be considered, ripening and weather conditions dominated the decision of the official beginning of the vine harvest (also emphasised in the town protocols: KTCP: 25 June 1672). As such, in general the reasons of changing or postponing the harvest date were mainly related to natural factors—primarily to weather and partly to other natural conditions. Even if human impact played some role (e.g. country fair, feast days etc), its rare influence did not affect the harvesting date by more than a couple of days, and thus, compared to natural factors, its significance was somewhat marginal. These conditions were demonstrated by the instruction of the town council, as a strong tradition which was also generalised and fixed for the future (KTCP: 27

Nov. 1716): ’As far as vine is concerned, similarly to the practice in the neighbourhood, we always have to keep ourselves to the weather conditions.’

Wine quality

Since in our study period the town primarily lived on the income derived from wine export towards such areas as Silesia, Prussia, Saxony and Austria (e.g. Szövényi 1965, 1966–1970), wine quality had special importance, and thus it was documented several times in the town council protocols and by contemporary authors such as Matthias Bél from the late sixteenth century onwards. However, a systematic set of data is available only from 1740 in the *Book of Vinesprouts*. In this book, apart from other phenological parameters, information is provided for each year, describing how good or bad (sweet or sour) the vine/ wine was in the actual year. Based on this descriptive qualitative information, we used the following 5-point index system: very bad/sour (1), worse than average, not good, bad (2), average (3), good, better than average (4) and very good/sweet/strong (5). Although other scaling systems (e.g. 3-point: Pfister 1984; 4-point: Brázdil et al. 2008; 7-point: Strömmer 2003) are also utilised in the scientific literature, in our case the (higher) number of years with very bad wine, and the very exceptional cases of years with extreme qualities in the descriptions, did not provide enough reason for applying scaling methods other than the 5-point one. In the case of vine quality, apart from May–July, the importance of August–October temperatures is much more pronounced than that of vine harvest date series (also emphasised by Péczely 1982).

Although the same information is provided concerning the harvested amount in each year, similarly to quantitative tithe information, this type of information had to be excluded from the present reconstruction due to low correlation values with measured temperature.

Dates of collecting vine and grain tithes

Town citizens paid their wine and grain taxes to the bishop of Győr (see, e.g., Bél 1984), and the town authority was responsible to collect it each year until 1848. Information on the circumstances and the way of tithe collection procedures and their documentation are quite well-known due to the fact that, especially in 1672, very detailed descriptions of the precisely defined, long-term (’*ex antiquo usu*’) unchanged and ’obligatory’ tradition of wine and grain tithe collection was described to the Royal Chamber. These detailed descriptions and instructions were, for example, included in the town council protocols (25 June and 14 July 1672). Grain tithes were collected in the field, while vine tithes were taken after people pressed out the juice. Moreover, almost every year, mainly again in the town council protocols and partly in the town master’s accounts, information was provided about circumstances of tax-collection, lunch payments of tax-collectors, some tithe-auctions, etc.

In general, this type of information is rather similar to dates of grain tithe auctions, first described in Switzerland (Pfister 1979). Even if collection dates of vine and grain tithes are mainly dependent on ripening and harvest dates, other parameters such as the end of grain harvest or vintage together with the end of pressing out of the juice also had to be accounted for. Autumn weather conditions unfavourable for transportation (rain, bad roads, etc.) and sometimes other uncertainties (e.g. disease, feasts, security questions) also played some role in defining the date for conscription of individual taxes. Nevertheless, due to the fact that the presently available two series are based on the actual dates of defining annual tax which was carried out in the town, transportation and other problems will have caused less significant delays.

Homogeneity issues: vine and grain types and management throughout the study period

Predominant vine types and conservative management practices: the study period and beyond

On the basis of the data available in the 1451-urbarium of Kőszeg (G-Güns), in the mid-fifteenth century the area covered by the vineyards was estimated to be ca. 390 ha, in 1552 ca. 357 ha (Bariska 1998), around 354 ha (1738) and then 372 ha in 1745 (Promontorial conscriptions 1738; Szövényi 1966–1970; Bariska 2001). According to the cadaster survey carried out in 1845, the extent of vineyards was still 356 ha. At the same time, the extent of arable lands was 631 ha (Fényes 1851). The area of vineyards was still similar (348 ha) in the mid-1870s (Chernel 1877), when a rapid reduction started, continuing into the twentieth century (Bariska 2001). Thus, the extension (and location) of vineyards did not change significantly throughout the study period. Wine-related information always played an important role in administrative documentation, especially because the town itself also possessed a large number of vineyards in various locations. The vineyards, owned by the town, were usually the places where the vine harvest was initially started by the hillmaster and vine shepherds, while ’common’ vine harvests usually started one or two days later.

When, in the early eighteenth century, Bél (1984) described the Kőszeg wine region, he not only provided information concerning his own period but, as he himself mentioned, described the long-term tradition. Thus, a rather detailed documentation of vine management traditions and techniques are available, among others, related to methods of wine production, soils, location of vineyards, risks of wine production with special emphasis on weather, vine types, circumstances concerning the harvest (timing, way of harvesting, location and extension of vineyards, etc.). Many of his descriptions are supported by the detailed documentation, available in the local administrative documentation, namely in the town council protocols, the *Book of Vinesprouts* and the accounts of the town. All these details provide us with evidence concerning a rather uniform management practice which had changed little over space and time.

Changes in vine type affect the climatic interpretation of the data. Therefore, determination of the main vine types and their biological response to climate is important. Twentieth century vine types of the Kőszeg region, for example, have vine ripening and grapevine harvest significantly (weeks) earlier than vine types of the 'traditional' (pre-late nineteenth century) period. The main vine types, mentioned in the (seventeenth–)eighteenth and nineteenth century sources of Kőszeg wine production (Table 1), are traditionally wide-spread and provided the basis of white wines, either in the western parts or in the whole Carpathian Basin (Kozma 2000; Hajdu 2003). Similarly to earlier periods, in the 1830s and 1870s, Furmint and Zirfandel were still mentioned as the most common vine types of the region (Schams 1833; Chernel 1877), but apart from that, the growing importance of other (also red) wines can be detected in the second half of the nineteenth century (e.g. Great Burgunder, Riesling, Tramini). Although no detailed information is available about the vine types of the area before the early eighteenth century, traditionally in vine plantations, the sticks from local vinestocks were used (Bél 1984), which means that the same vine types were also predominant in at least several decades prior to the description. Thus, concerning prevailing vine varieties, the area was quite conservative up to the late nineteenth century, and external impacts such as new varieties clearly played a marginal role (see also Fényes 1851) and therefore phenophases, quality and quantity of vines were dependent on the same vine types (Appendix Table 4).

The (biological) full ripening of these, 'traditional' vine types occur approximately at the same time: in early to mid-October (Hajdu 2003). This phenological information is in good agreement with the information kept in the town council protocols of Kőszeg, where hillmasters and the mayor usually reported the full ripening of grapes around early or mid-October, when decisions about the actual vine harvest (starting date, preparations, etc.) were made. When first ripening is mentioned in connection with the election of vine shepherds (around 10 August), Zirfandel with its somewhat earlier ripening appeared in the town protocols (KTCP 17 Aug. 1721: 'cirfandli', 10 Aug. 1739: 'Czirfandel'). Among the grapes harvested for producing wine, Zirfandel might have played an important role in defining the starting date of grape ripening. In traditional wine production, unlike today, Kőszeg wines were predominantly white ones. This situation remained approximately the same until the late nineteenth century (see, e.g., Bél 1984; Schams 1833; Fényes 1851; Chernel 1877). Kőszeg wine as a 'trade-mark' often meant a mixture or marriage of the juice or wine of these different types (Bél 1984), which is important in understanding quality descriptions and judgements, similarly documented in the *Book of Vinesprouts* from 1740 onwards. A gradually growing importance of red wines can be followed especially from the mid- and late nineteenth century (e.g. Chernel 1877).

What do we know about grain: predominant cereal types

Rather precise information is available concerning harvested grain types due to the fact that in almost each case, while defining the share of harvesters, the harvested grain types were listed in the town council protocols. In the tithe accounts, only the word 'grain' (H-'gabona', G-'traidte') appeared to denote taxation. Nevertheless, more information on the harvested grain types was described in the town

Table 4 Reported main and rare vine types in Kőszeg: eighteenth and nineteenth centuries

Year	Main vine/wine types	Other vine/wine types mentioned	Source
ca. 1730	Cyrobotrus/Zyrfandel (Zirfandel), Zapfel (Furmint), Muscatel, Albula (White Grape), Augusta (Gohér) – all white wines	Zoller, die Steierische Weinbeere, Geisdutten, Lampertweintraube – all white wines	Bél 1984
1833	Furmint, Zirfandel		Schams 1833
1845	White wines		Fényes 1851
1877	Furmint, Zirfandel	Red wines: Blue Frankish, Great Burgunder, Riesling, Tramini etc.	Chernel 1877
1930	Red (e.g.): Great Burgunder, Blue Frankish. White (e.g.): Riesling, Furmint		*Book of Vinesprouts* n.d.

council protocols while ordering the annual share (in crop percent) of harvesters: winter crops and spring crops were harvested each year, one after the other, respectively. Winter crops such as wheat and rye were detailed in the protocols every second or third year from 1650 until 1760. Spring crops were mainly oat and barley (KTCP, e.g. 1650, 1653–1654, 1660, 1663–1664, 1709, 1725–1726, 1744, 1760), but sometimes also buckwheat (KTCP, e.g. 1726, 1731–1732, 1739–1740) and millet (KTCP, e.g. 1732) were mentioned. From the late eighteenth century, maize also appeared as part of the crops harvested (KTCP, e.g. 1794). Although no direct information is available concerning the quantity sown and harvested proportions of different grain types, wheat had usually the greatest importance in the area, followed by rye and barley and then oats together with other spring crops (e.g. SzTCP, 1790, 1840). Even if there is not always detailed information available concerning management and cereal types, the town protocols and town management accounts similar to the case of vine, show rather conservative and predominantly unchanged agricultural practices through the study period.

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