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ORIGINAL PAPER

The *Book of Vinesprouts* of Kőszeg (Hungary): a documentary source for reconstructing spring temperatures back to the eighteenth century

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Abstract Following an age-old tradition, since 1740, in the town of Kőszeg in western Hungary, samples of grapevine shoots are annually harvested on St. George's Day, 24 April, and then are pictorially reproduced in the so-called *Book of Vinesprouts*. Given the strong relationships between temperature and grapevine phenology, the book represents a potential source for reconstructing past spring temperatures. However, this document has been little utilized so far, due to high varietal heterogeneity and lingering uncertainty regarding cultivar identity. This research developed an approach to address these difficulties, by means of a single-cultivar-based modeling analysis, associated with a set of alternative hypotheses about cultivar early development for the period to be reconstructed. Each hypothesis allowed the calculation of a different past temperature reconstruction, which was evaluated against contemporary independent observational data. The results showed that all the development stages recorded before 1900 were compatible with a vine type with a very low heat requirement for bud burst. Estimates were derived from a model calibrated on a subset of drawings of unknown cultivars executed between 1875 and 1898. The model based on this data subset was the only one giving a consistent reconstruction of spring temperatures, expressed as accumulated growing degree days going back to 1740. Although some uncertainty still exists regarding the reconstruction, the research shows that the *Book of Vinesprouts* contains generally consistent information about spring temperatures for a period of over 269 years for this region of Hungary.

Keywords Grapevine · Phenology · Spring temperatures · Climate change · Hungary

Introduction

Climate change studies require extended weather recordings in order to detect and characterize long-term trends. However, reliable instrumental observations became available only in the nineteenth century, limiting the time scope of the analysis. In order to extend climate datasets to pre-instrumental times, it is therefore necessary to reconstruct climate variables using proxies, which can be natural (e.g., tree-rings, pollens, stalagmites, etc.) or human-made (e.g., documentary data, chronicles, observations of climate-dependent phenomena such as glaciers, records of animals/plant phenology, etc.). The latter include phenological observation records from cultivated plant species, which are available from a high number of sites (Post and Stenseth 1999; Menzel 2003; Helama et al. 2004; Holopainen et al. 2006; Rutishauser et al. 2007). Due to its historical economic importance, the grapevine has been one of the most-utilized crops in both climate reconstruction and climate assessment studies (Le Roy and Baulant 1980; Jones and Davis 2000; Chuine et al. 2004; Meier et al. 2007; Daux et al. 2012). Grape harvest dates, in particular, have been used for spring-summer temperature reconstructions, since grape growth and ripening depend on temperature accumulation integrated over the entire vegetative period and correlate strongly to the harvest date at the end of the growing season (Burkhardt and Hense 1985; Souriau and Yiou

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2001; Chuine et al. 2004; Menzel 2005; Meier et al. 2007; Rutishauser et al. 2007; Brázdil et al. 2008; Mariani et al. 2009; Maurer et al. 2009).

The *Book of Vinesprouts*

In the Hungarian town of Kőszeg (47° 23′ N, 16° 32′ E), located 3 km from the Austrian border (Fig. 1), viticulture has long been a prominent activity, whose importance is underscored by an age-old tradition. On St. Georges Day (24 April), which used to be the election day of the local authorities, it is customary to collect the first grapevine shoots from the vineyards in neighborhoods surrounding the town. Once collected, the shoots are brought to the mayor who then examines the shoots to forecast the upcoming grape and wine yield. While a written record of this tradition began as early as 1568, the shoots were pictorially reproduced each year in a book starting in 1740, along with notes concerning the harvest and the wine characteristics. The book is now known as the *Book of Vinesprouts* (BOV) and is preserved in the Kőszeg Jurisics Town Museum. It contains over 1000 drawings of shoots or buds at various development stages. Shoot drawings cover the 1740 to present period, except for a total of 53 years, mostly before 1850, when they were replaced by short descriptive annotations. Since there is a strong relationship between grapevine shoot development and thermal summation (e.g., Moncur et al. 1989), it is easy in principle to envision a reconstruction of past temperature summations by inverting conventional growing degree-day (GDD)-based phenological models calibrated on historical temperature records. An important reason for studying shoot phenology is that it allows for the reconstruction of spring temperatures, which are typically not available in most natural and documentary proxies, since the climatic signal for spring and autumn temperatures is not as strongly expressed as it is in the winter and summer seasons (Brázdil et al. 2005; Xoplaki et al. 2005).

Spring phenological events are also more informative than grape harvest dates (Chuine et al. 2004; Brázdil et al. 2008), because the information provided by the latter can be affected and confused by changes in wine-making technologies, fruit health nearing harvest time, and grower/producer ripeness goals. The relationship between development stage and temperature summation is also likely to be more accurate in spring than at harvest, because it is calculated over a shorter period of time, with little error accumulation. In this respect, the Kőszeg shoots have the additional advantage of having been always collected on the same date, thus allowing for a homogeneous comparison among years.

However, despite its potential interest, very few studies have so far utilized the book for climate reconstruction purposes (e.g., Střeštík and Verő 2000). The reason lies mainly in the fact that different vine types have been reproduced in the book over the years, thus making the series highly heterogeneous, and because until 1925, the name of the cultivar was never recorded, rendering it impossible to associate them with a vine type with known phenological response. These problems were recently evidenced by Kiss et al. (2010), who reconstructed past May–July temperatures for the Kőszeg area, using a set of other documentary data (i.e., wheat and grapevine harvest records), which did not include the BOV because of its high heterogeneity and uncertainty level.

The purpose of this research was to revisit the BOV as a potential source for past climate reconstruction, addressing the heterogeneity problem through a single-cultivar-based modeling to capture varietal time-course variation. On the ground of experimental evidence indicating the existence of a linear relationship between the rate of shoot elongation and

Fig. 1 Location of the towns of Kőszeg, where the shoots were harvested and reproduced in the *Book of Vinesprouts*, and of Szombathely, the nearest location (18 km) with long-term temperature data available. Both regions are in the Vas region of Western Transdanubia in Hungary

temperature, we associated each phenological stage with a corresponding thermal sum, based on the well-established growing degree-day (GDD) modeling approach, and we then used it to derive spring temperature estimates from the shoots going back to 1740.

The problem of associating an appropriate GDD sum with pre-1925 unknown genotypes was handled by setting up a set of alternative hypotheses concerning their heat requirements for bud burst. The probability in favor of any of the potential hypotheses is discussed in relation to clues derived from the exploratory analysis of the BOV and by comparison with contemporary observational and reconstructed data.

Materials and methods

The BBCH-based modeling

A previous attempt to reconstruct past temperature from the Kőszeg drawings utilized a model based on shoot length in relation to temperature (Střeštík and Verő 2000). That approach presents disadvantages, since it cannot be used on the first stages of bud opening and initial development—which on the other hand are often pictured in the BOV—hence foregoing a considerable amount of available information.

We preferred instead to model shoot development using the Bundessortenamt and Chemical Industry (BBCH) scale as described by Lorenz et al. (1995), whose original version is reported in Table 1, associating each discrete stage to a thermal sum. This could be done by averaging the GDD calculated for the BBCH observations available for each discrete stage. Unfortunately, the BOV does not provide enough repetitions for each BBCH stage and cultivar to establish a robust GDD-BBCH one-to-one table. To circumvent this issue, the BBCH scale was treated numerically, transferring BBCH decimal codes to a quantitative measurement of development. This involves the assumption that shoot elongation stages, as identified by BBCH codes, are separated by equal thermal time intervals, which is consistent with experimental data, at least for the steps after the first leaf appearance (Lebon et al. 2004). Furthermore, with respect to the original scale, we introduced the intermediate stages, "2," "4," "6," "8," and "10" to ensure continuity from "00" to "20," thus allowing for mathematical treatment of the scale, e.g., for calculating averages, which can take any values between 0 and 20. This modified scale also allowed a higher flexibility in classifying the pictorial representations. Once the BBCH scale was appropriately modified, the following linear model was applied to the available GDD-BBCH pairs:

$$\mathrm{GDD} = a \cdot \mathrm{BBCH} + b$$

where a and b are empirical coefficients.

In this manner, stages with few or no observations could be identified by linear interpolation. Although not commonly used, similar BBCH-based modeling experiences have been conducted on both annual plants (e.g., Royo-Esnal et al. 2012) and on grapevines (Cola et al. 2012), providing a very useful tool to model shoot development. A preliminary assessment of the feasibility of this method was conducted on data drawn from two independently obtained phenological datasets from northeastern Italy, on the Chardonnay cultivar:

1. A 6-year series of field observations at the experimental vineyard of CRA-Centro di Ricerca per la Viticoltura (located at Susegana, 45.85° N, 12.25° E), from 2008 to 2013 (own data);
2. A 26-long year series of observations at the experimental vineyard of CECAT - Centro per l'Educazione, la Cooperazione e l'Assistenza Tecnica (located at Istrana, 45.68° N, 12.10° E). These observations were limited to the bud burst phase, which was recorded at the BBCH stages of 5, 8, and 13 (own data).

Table 1 Description of the BBCH scale, as in Lorenz et al. (1995)

Growth stage	Code	Description
Sprouting/bud development	00	Dormancy: winter buds pointed to rounded, light or dark brown according to cultivar; bud scales more or less closed according to cultivar
	01	Beginning of bud swelling: buds begin to expand inside the bud scales
	03	End of bud swelling: buds swollen, but not green
	05	"Wool stage": brown wool clearly visible
	07	Beginning of bud burst: green shoot tips just visible
	09	Bud burst: green shoot tips clearly visible
Leaf development	11	First leaf unfolded and spread away from shoot
	12	2 leaves unfolded
	13	3 leaves unfolded
	14–20	4–10 leaves unfolded

BBCH classification and explorative analysis

For this research, a high-resolution digital scanning of the BOV was executed in 2009; therefore, this analysis covers the 1740 to 2009 time period. All drawings were then visually classified according to the modified BBCH scale. For a total of 53 years, no drawings were made, so the short descriptive notes were utilized instead; some of these descriptions were precise enough to allow a plausible estimate (e.g., *shoots one foot long*), while others were more vague, requiring some interpretation. To give some example, where statements such as *nice shoots* were found, we took the average of the best five shoots in the previous ten years, assuming they corresponded with the likely experience of the anonymous editor at that time. Expressions such as *there were nothing but just a few shoots* were interpreted as beginning of bud burst, and given a BBCH score of 11. In most cases however, especially before 1850, there was just the bare annotation *no shoots*. This was interpreted as all buds closed, which however could stand for every stage between 0 and 10. Here, we arbitrarily assigned the BBCH value of 5, average of the 0–10 pre-shooting stage. The postulated assignment is to be considered as a low-end cutoff, since the absence of shoots could correspond to variable lower temperatures and stages. For 7 years (1770, 1771, 1772, 1773, 1785, 1786, and 1787), there were neither drawings nor descriptive information, and for these years we assumed the *no shoots* hypothesis.

Temperature data

The nearest meteorological recording station with a sufficiently long history is from the town of Szombathely (47.23° N, 16.62° E), 18 km from Kőszeg (Fig. 1). The 1901–2000 daily temperature series was available from the website of the Hungarian Meteorological Service (http://www.met.hu/eghajlat/magyarorszag_eghajlata/eghajlati_adatsorok_1901-2000/Szombathely/). From 2001 through 2009, daily temperatures were available from the historical section of the www.freemeteo.com service (both sites last accessed in February 2013).

Data from 1875 to 1900 were also available, but only as mean monthly temperature from the records of the HistAlp project (Auer et al. 2007), accessible at the Website http://www.zamg.at/histalp/ (last access, February 2013). From this data, we estimated a surrogate daily temperature through linear interpolation after having assigned the mean monthly temperature to the mid-month day.

Modeling analysis

The objective of the modeling analysis was to establish reliable GDD-BBCH relationships from the data derived from the BOV drawings in conjunction with the available temperature data. This was done on a single-cultivar basis, since this allowed the capture of the effect of genetic diversity across the time-course variation of the relationship.

Although a total of 40 varieties are mentioned in the BOV (Table 2), only those with at least five occurrences were considered for fitting the GDD-BBCH linear model. The analysis was conducted also on data derived from unknown cultivars aggregated using different grouping criteria (see below). Although shoots were sampled from various fields around Kőszeg, we pooled the data into one single dataset for each cultivar. This pooling assumed that the locality effect on shoot timing was negligible because all the sampling fields used historically were located in the hillsides within approximately 1-km radius of the middle of town.

The observations between 1875 and 1898 were made on unspecified cultivars, but in a period where temperature measurements were available, hence they were collected in a

Table 2 List of the grapevine cultivars mentioned in the *Book of Vinesprouts*

	Name	Number of occurrences	First mention	Last mention
1	Unknown	314	1744	1898
2	Burgundi	107	1925	2005
3	Kekfrankos	101	1912	2007
4	Nagy burgundy	59	1954	1971
5	*feher*	54	1899	1939
6	*fekete*	50	1899	1929
7	Olaszrizling	50	1926	2005
8	Chasselas	49	1934	1991
9	Zweigelt	49	1986	2007
10	Furmint	31	1925	1981
11	Rizling	16	1934	1985
12	Cserszegi Fűszeres	16	1990	2006
13	Bianka	15	1990	2007
14	Oporto	15	1965	2007
15	Muskotaly	8	1935	1985
16	Banati rizling	6	1935	1975
17	Zold Muskotaly	6	1957	1992
18	Kiralyleanyka	6	2002	2006
19	Leanika	4	1965	1987
20	Zala Gyöngye	4	1982	1999
21	Kövidinka	3	1965	1968
22	Mezesfeher	3	1925	1927
23	Rizling Szilvani	3	1984	1999
24	Zold Szilvani	3	1964	1986
25	Blauburger	2	2006	2007
26	Erzsebet kiralyne	2	1968	1969
27	Izabella	2	1937	1964
28–40	Others (cultivars with only 1 mention each)	16		

separated group, although it cannot be excluded that the observations came from different vine types. From 1899 to 1925, the drawings were broadly divided into *feher* (“white grape”) and *fekete* (literally “black” grape). After 1925, the drawings were labeled with the cultivar name, and it was possible to aggregate them into more explicitly defined groups. The accumulated GDDs from 1 January to 24 April were then calculated for each available year from interpolated (1875–1899) or actual daily temperature data (1900–2009). Although it is usual to calculate GDD using a base temperature (T_b) of 10 °C (Jones et al. 2010), different values have sometimes been reported (Moncur et al. 1989; García de Cortázar-Atauri et al. 2009). Having many cultivars to model, it is likely that there could be differences in response to temperature, which could be accounted for by different T_b values. In order to assess the most appropriate T_b for each cultivar, we iterated the calculation of regression parameters and the determination coefficient for all values between 0 and 10 °C at 1 °C increments. For each cultivar, the T_b value which maximized the R^2 of the regression was taken as the optimal T_b value. Once the optimal T_b was found, only those cultivars with a R^2 greater than or equal to 0.5 were kept for the successive steps in the analysis. Finally, since a unique T_b was necessary to perform past GDD estimation, which was based on aggregated estimates of multiple models (see below), the value giving the highest cross-cultivars average R^2 was adopted for all cultivars.

Past temperatures estimation

Once a GDD-BBCH model was established, past spring temperature reconstruction was performed by associating the GDD summation values to each discrete BBCH stage. Since the earliness of the cultivars employed before 1925 is unknown, a hypothesis has to be made as to whether one or more of the developed models are suitable to be applied to the drawings from that period. From the results of the exploratory analysis and the modeling work, a number of alternative models with different earliness were examined, under the assumption that the cultivars actually used in the past had similarity with at least one of them. Clues to identify the most suitable model are expected from the exploratory analysis itself and from the comparison with contemporary documentary and instrumental data, where available. Each of the single-cultivar-based models obtained from the BOV could be a candidate for past temperature reconstruction. To limit the number of hypotheses, the cultivars were aggregated into larger groups with similar development precocity. The grouping criterion was based on the estimated GDD obtained from each GDD-BBCH model in correspondence with the BBCH-18 grade, which is the highest one observed in the entire BOV. An “early” group was defined as the set of cultivars needing less than 200 °C day^{-1} to reach BBCH-18, while the “medium” and “late” group GDD ranges were defined as those requiring between 200 and 250 and >250 °C day^{-1}, respectively (Table 3). A GDD-BBCH relationship was derived for each group in order to calculate the GDD for each BBCH grade. Mean values and confidence limits of the estimated GDD were assessed by means of a bootstrapping procedure, which ran as follows: for each cultivar, the available GDD-BBCH pairs were iteratively re-sampled with replacement, and the regression parameters were recalculated at each step, as well as the estimated GDD-BBCH pairs. The procedure was iterated 10,000 times and a GDD distribution was generated for each BBCH grade for each cultivar. Results from each cultivar were then pooled into the earliness group they were assigned to, and for each BBCH grade the mean GDD and the 95 % confidence interval limits were calculated. For each precocity hypothesis, a GDD time series from 1740 to 1874 was therefore reconstructed by simply assigning to each BBCH stage the corresponding calculated GDD and confidence limits.

Validation against contemporary instrumental and reconstructed data

A number of historical datasets from European localities, to be used as reference data, were obtained from the HistAlp project (Auer et al. 2007) as monthly means records, which were converted into daily time series through linear interpolation, then used to generate GDD time series at the 24th April.

A further reference dataset was the historical series from the Clementinum observatory in Prague (Brázdil et al. 2012), available as daily measurements, which was downloaded from the European Climate Assessment and Dataset Website (http://www.ecad.eu. Last access, February 2013).

The longest series was from Milan, starting in 1763 and the shortest was that of Linz, starting in 1818. The farthest locality

Table 3 Aggregation of cultivars based on the bud burst earliness expressed as the amount of GDD (T_b=6 °C) required to reach the BBCH stage 18 according to each single-cultivar GDD-BBCH model

Group	Cultivar	GDD-BBCH$_{18}$
Early	Unknown	171.6
	feher	201.3
	fekete	213.2
	burgundi	228.5
Medium	*furmint*	233.3
	rizling	236.9
	olaszrizling	239.9
	chasselas	245.8
Late	*kekfrankos*	254.1
	zweigelt	268.5
	cserszegy_fuszerer	285.7
	bianka	307.3

was Karlsruhe, Germany, 630 km from Kőszeg. The Pearson's correlation coefficient between the Szombathely series and each reference series were calculated and checked for statistical significance with the Pearson's product moment correlation coefficient test. For all localities, the correlation resulted as significant ($p<0.001$, not shown). It is assumed that the same correlations hold also for the pre-1875 period, which implies that the same mean temperature difference calculated on measured data (expressed as accumulated GDD) is expected between estimates for Kőszeg and reference measured data. The statistical significance of this difference was assessed by the Wilcoxon rank sum test. Both Pearson's correlation coefficient test and Wilcoxon rank sum test were performed with the R statistical software v. 2.15 (R Core Team 2014).

Results

BBCH-based modeling

Figure 2 displays the relationship between accumulated GDDs (T_b=10 °C) and the BBCH stage for Chardonnay, observed during previous research (unpublished own data). The pooled observations exhibited a clear linear relationship, with a high determination coefficient (R^2=0.83). Observations at stages 1 to 3 (Fig. 2, square symbols), being poorly correlated, were not included in the model, while a stage "4" was not recorded here, so it was not included either. This preliminary result showed that the BBCH scale can be safely assumed to vary linearly with thermal time in the interval between 5 and 20 BBCH stages, a range sufficiently large to cover the majority of BOV drawings.

Modeling analysis

The BBCH values derived from all the BOV drawings were plotted against time and grouped into five distinct categories, as showed in Fig. 3:

1. Drawings with clear indication of the cultivar (closed circles)
2. Drawings with no indication of cultivar (open circles)
3. Drawings with a generic indication of the cultivar, i.e., *feher* (=white grape) and *fekete* (=black grape) (gray circles).
4. Drawings with no indication of the cultivar, but with temperature data available (dark gray circles)
5. Hypothetical BBCH values based on verbal descriptions, and with no indication of cultivar, including "no shoots" years which were arbitrarily assigned the 5 BBCH grade (gray triangles).

Overall, there is a clear tendency for a decrease in vine development on the 24 April, from roughly a mean BBCH value of 14 in the 1740–1780 interval, to the value of 8 between 1940 and 2009. After 1950, the within-year variability increased as a higher number of varieties was sampled each year.

The mean BBCH stage calculated for each year was compared with an estimated one obtained by applying the independently obtained regression equation for GDD vs BBCH for Chardonnay in Fig. 2, to the instrumental temperature series available (1875–2009). Being derived from a single-cultivar model, this second BBCH time series represents the variation in vine development which can be explained only by changing temperatures, while the variations observed in the Kőszeg series depended on both temperature and genotype variations. The results, expressed as 10-year moving averages,

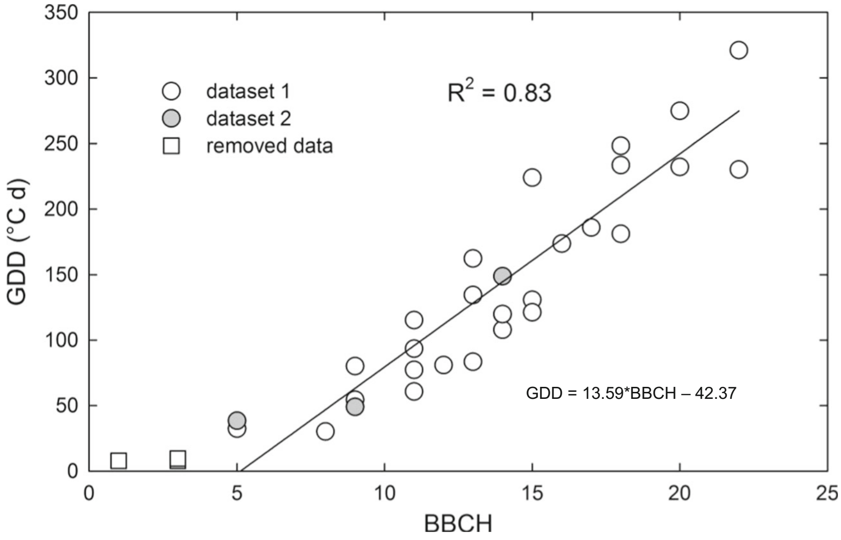

Fig. 2 Relationship between GDD (base temperature=10 °C) and the observed phenological stage in the modified BBCH scale (see text), from two independent datasets experimentally obtained from two locations in north eastern Italy (cultivar 'Chardonnay')

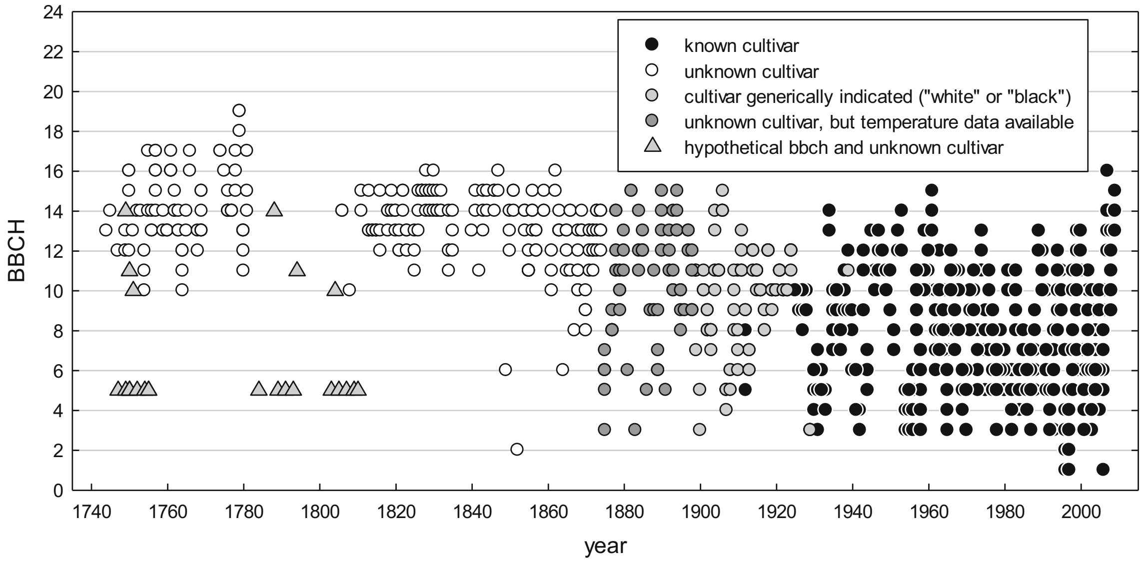

Fig. 3 BBCH (modified scale) values derived from drawings or descriptive notes in the *Book of Vinesprouts* (1740–2009) and classified according to the degree of information available about each observation

are displayed in Fig. 4. While the estimated Chardonnay development stage tends to increase over the years (gray line), i.e., towards earlier bud burst and higher BBCH values, the BOV-based series shows an opposite trend towards less developed shoots, i.e., towards delayed bud burst (black line).

Single-cultivar modeling analysis

Three cultivars out of fifteen were discarded because of poor correlations between GDD and BBCH (not shown), while the others were optimized with respect to T_b. The variance explained by BBCH variation across all models was between 0.53 and 0.85 (Table 4). The T_b giving the highest mean average R^2 across all the cultivars (=0.63) was 6 °C, which was adopted for the subsequent analysis. At this T_b value, all regressions were found highly significant ($p<0.001$), except for 'Banati rizling' and 'Muskotaly', which had higher p values, respectively, 0.067 and 0.045, due to the lower number of observations. Figure 5 displays the GDD-BBCH plots for the known cultivars (post-1925), while those in Fig. 6 were derived from the generically indicated cultivars, *feher*, *fekete* (1899–1924) and the "unknown" ones for the 1875–1898 period. The shoots labeled *feher* and *fekete* were taken always from the same four vineyards, and from a visual assessment of the plots, it appears that these refer to two groups having a different GDD-BBCH relationship, indicated by white and gray symbols. Only one of these two groups showed a consistent linear variation with temperature (white symbols), and

Fig. 4 Variation of the average observed BBCH (modified scale) from 1740 to 2009 and of the estimated BBCH obtained through a GDD-BBCH model calibrated on the 'Chardonnay' cultivar with independent data (10-year moving averages)

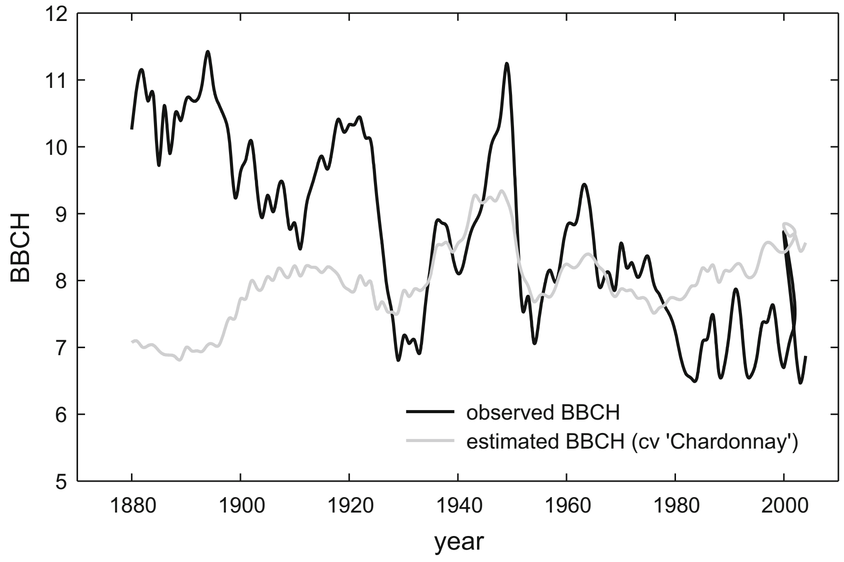

Table 4 Optimization of the base temperatures (*Tb*) for GDD calculation

Cultivar	T_b (°C)											p value (T_b=6 °C)
	0	1	2	3	4	5	6	7	8	9	10	
Banati rizling	0.41	0.42	0.42	0.42	0.46	0.52	0.61	0.71	**0.72**	0.56	0.38	0.067
Bianka	0.67	0.69	0.72	0.76	0.79	0.81	**0.85**	0.81	0.69	0.53	0.41	<0.001
Burgundi	0.42	0.45	0.48	0.52	0.53	**0.53**	0.53	0.49	0.45	0.37	0.30	<0.001
Chasselas	0.66	0.67	0.71	0.74	0.77	**0.79**	0.77	0.74	0.67	0.56	0.45	<0.001
Cserszegy fuszerer	0.50	0.53	0.55	0.59	0.62	0.66	0.71	**0.72**	0.62	0.45	0.29	<0.001
Furmint	0.45	0.49	0.52	0.56	0.58	0.61	0.64	**0.67**	0.64	0.56	0.45	<0.001
Kekfrankos	0.53	0.55	0.56	**0.58**	0.58	0.58	0.56	0.53	0.48	0.41	0.34	<0.001
Muskotaly	**0.61**	0.59	0.56	0.55	0.52	0.52	0.52	0.49	0.44	0.29	0.18	0.045
Nagy burgundy	0.71	0.74	0.77	0.81	0.85	**0.85**	0.83	0.79	0.72	0.62	0.46	<0.001
Olaszrizling	0.58	0.61	0.66	0.69	0.72	**0.72**	0.71	0.67	0.62	0.52	0.41	<0.001
Rizling	0.32	0.36	0.41	0.48	0.52	0.56	**0.58**	0.56	0.52	0.44	0.34	<0.001
Zweigelt	0.55	0.58	0.59	0.62	0.64	0.66	0.71	**0.72**	0.69	0.59	0.48	<0.001
feher	0.17	0.20	0.24	0.31	0.37	0.44	0.50	0.53	0.54	0.56	**0.56**	<0.001
fekete	0.12	0.16	0.22	0.29	0.35	0.42	0.49	0.53	0.54	0.58	**0.59**	<0.001
Unknown (<1899)	0.46	0.52	0.53	0.52	0.49	0.45	0.40	0.34	0.28	0.20	0.14	<0.001
Mean	0.48	0.50	**0.53**	0.56	0.59	0.61	**0.63**	0.62	0.57	0.48	0.39	

The determination coefficients (R^2) of the GDD-BBCH regression line were calculated varying T_b in the 0°–10 °C interval. The highest values obtained for each cultivar are shown in bold characters. The rightmost column gives the statistical significance of linear fitting for T_b=6 °C

they were retained for further analysis. As far as the unknown observations that overlap the instrumental temperature period (1875–1898), the GDD association with BBCH showed a significant linear correlation (r=0.68; p< 0.001 at the Pearson's product moment correlation test), although there is no way to assess whether these data refer to one or more cultivars.

Past temperatures estimation

The GDD series from 1740 to 1874 was reconstructed using the "early," "medium," and "late" earliness models. Figure 7 displays the series estimated with the former model, derived from the unknown observations (1875–1898), the data subset chronologically nearest to the target period. The reconstructed temperatures (accumulated GDD, T_b=6 °C) are expressed as anomalies with respect to the mean of the 1961–1999 period, which is 144.7 °C day^{-1}. The estimates are displayed both on a single year basis (solid black line) and as 10-year moving average (solid bold line), with 95 % bootstrapped confidence limits (dotted black lines); measured data are reported as gray lines.

Most of the reconstructed spring period is characterized by similar or cooler conditions than the reference baseline. The warmest reconstructed springs occurred in the period until 1782, where for 10 years temperature was above the reference line. During this period, in 1778, the most developed shoot of the entire BOV was painted, which reached the 18 BBCH stage, while three springs (1770, 1771, and 1773) did not reached the minimum threshold for bud burst.

The subsequent period, between 1783 and 1795, was the coldest one in the reconstructed series, where in 10 years out of 12 there were no shoots, and the 10-year moving average touched the lowest peak of all the series, in 1789.

The following years until 1812 showed a higher interannual variability, on average around 50 °C below the reference line.

Between 1813 and 1890, the interannual variability attenuated, but the 10-year moving average remained below the baseline, with a decreasing trend from around −20 to −50 °C.

Validation

Table 5 reports the results of the validation against the available reference localities. The third column reports the Pearson's correlation coefficients (c.c.) calculated between the Szombathely series and each reference dataset. The coefficients, which tend to decrease as expected with distance, are highly significant for all sites (p< 0.001, not shown). The "measured" column reports the average difference between the accumulated GDDs in Kőszeg and in each reference location, for the 1875–2009 period, when data are available for both measured locations. The "estimated" columns report the same difference for the 1740–1874 period, but calculated using Kőszeg estimates and measured data in the reference location. There is an estimated column for each of the

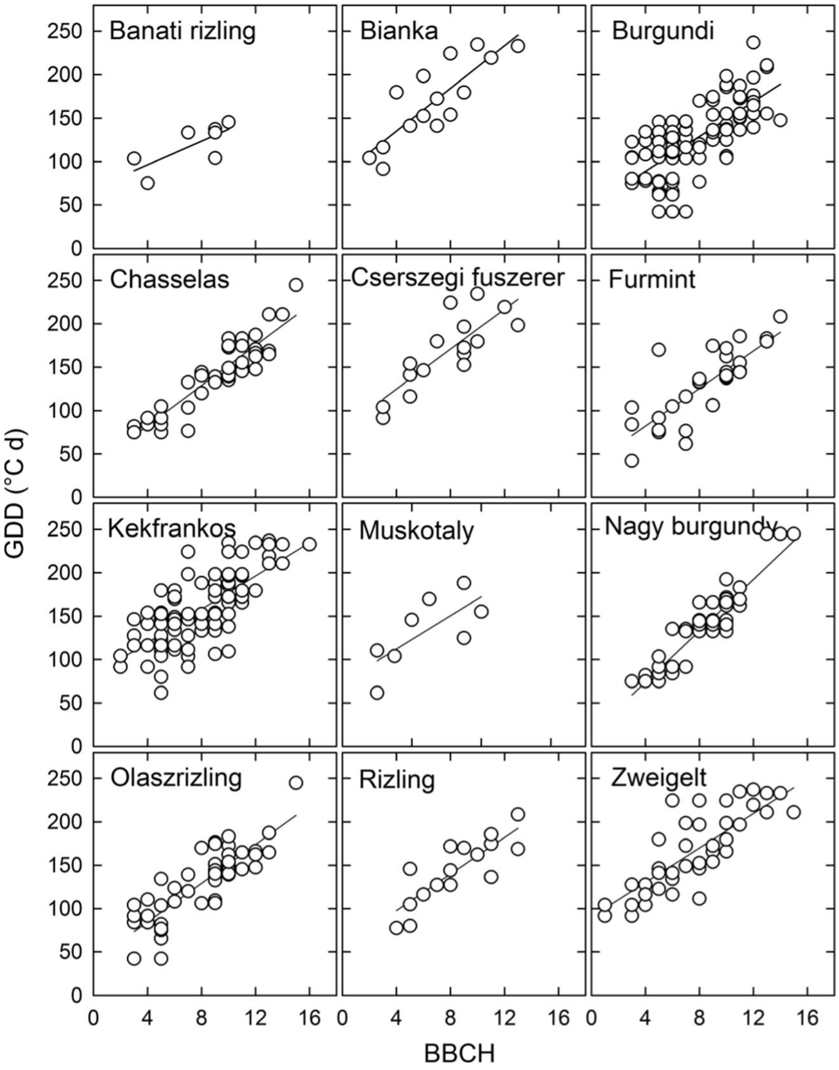

Fig. 5 Relationships between GDD and BBCH (modified scale) for 12 cultivars described in the BOV from 1925 to 2009

earliness hypotheses: early, medium, and late. The *p* values next to each GDD difference in the estimated columns are the outputs of the Wilcoxon rank sum test, assessing whether the estimated pre-1875 GDD differences are different from those calculated for the following period. The test for the early model returned no significant difference for all of the reference locations, since all *p* values ranged from a minimum of 0.091 (Kőszeg vs. Udine) to 0.999 (Kőszeg vs. Karslruhe). On the other hand, the pre-1875 estimates based on both the medium and late model resulted significantly different from those calculated for the post-1875 period for all locations. Therefore, since only the estimated GDD difference based on the early model proved to be similar to those calculated on measured data, this is the model providing the most plausible estimates of the 1740–1875 spring thermal regime in Kőszeg.

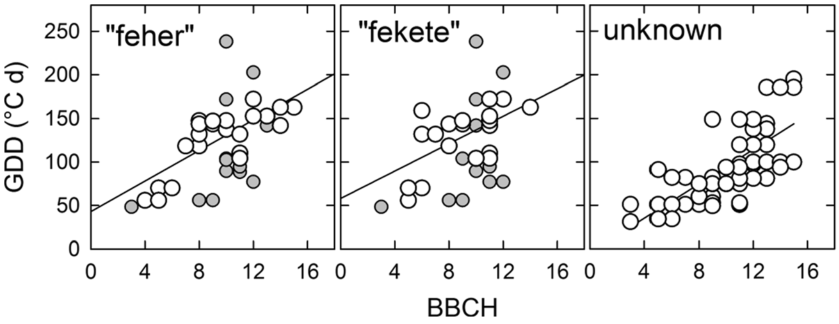

Fig. 6 Relationship between GDD and BBCH (modified scale) for three groups of cultivars appearing in the BOV, generically referred to as white (*feher*) or black (*fekete*) grapes, while the third group refers to the unknown cultivars (open symbols)

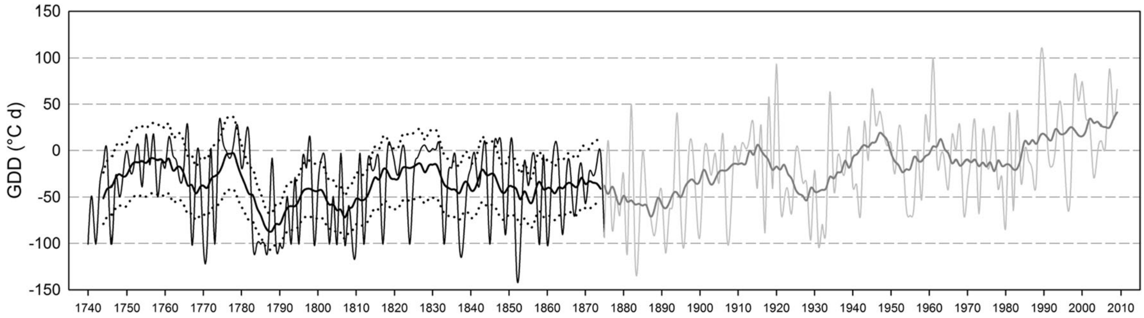

Fig. 7 Reconstruction of the GDD time series between 1740 and 2009, according to the highest earliness hypothesis (see text). GDD values are reported as anomalies with respect to the 1961–1999 period (mean value, 144.7 °C day^{-1}). *Black* and *gray solid lines* display reconstructed and measured series, respectively. The *solid bold line* is 10-year moving averages with 95 % bootstrapped confidential limits for the reconstructed period (*dotted lines*)

Discussion

Addressing the varietal heterogeneity and uncertainty in the BOV

The visual overview of the whole BOV pictorial information expressed in BBCH units (Fig. 3) provides a comprehensive assessment of the heterogeneity of data, as well as of the time-course variation of the shoot development precocity. The historical causes of such change are outside the scope of this analysis, but some plausible explanations can be nevertheless advanced. For instance, increasing preference towards cultivars ripening later may have been motivated by technical developments in wine-making. In addition, the advent of new pest or disease problems such as phylloxera (1880) and downy mildew (1878), or the change of national borders (1920) could have forced growers to switch to other varieties. Even the introduction of vines grafted on rootstocks, to reconstruct vineyards devastated by phylloxera, may have also contributed to the phenological shift. However, examination of summer and autumn temperatures during the last 200 years suggests that this shift could not have been caused by climate change, which would have stimulated a varietal adjustment to better meet climate conditions at ripening. From Fig. 8, showing the

Table 5 Validation of pre-1875 estimates against independent contemporary time series

Reference location	Available measures	c.c.	Average GDD difference between Kőszeg and the reference location						
			Measured 1875–2009	Estimated 1740–1874					
				Early model	*p* value	Medium model	*p* value	Late model	*p* value
Vienna (90)	1775–2008	0.84	97.7	97.1	0.957	151.3	<0.001	195.5	<0.001
Budapest (190)	1780–2007	0.81	82.7	82.7	0.548	136.7	<0.001	181.1	<0.001
Linz (194)	1817–2007	0.82	105.1	103.7	0.704	157.4	<0.001	201.9	<0.001
Kremsmünster (198)	1768–2007	0.82	115.7	113.1	0.334	167.4	<0.001	211.6	<0.001
Udine (290)	1803–2007	0.71	31.7	42.2	0.091	96.0	<0.001	140.5	<0.001
Prague (335)	1776–2005	0.84	1.4	6.0	0.195	60.3	<0.001	104.5	<0.001
Innsbruck (400)	1777–2007	0.71	107.7	104.7	0.600	158.8	<0.001	203.1	<0.001
Padua (420)	1774–2005	0.63	5.4	14.5	0.102	68.8	<0.001	113.0	<0.001
Verona (480)	1788–2007	0.71	15.8	15.0	0.870	68.8	<0.001	113.3	<0.001
Stuttgart (570)	1792–2007	0.70	98.6	95.7	0.747	149.6	<0.001	194.0	<0.001
Milan (605)	1763–2007	0.63	−24.5	−20.8	0.580	33.5	<0.001	77.7	<0.001
Karlsruhe (630)	1779–2008	0.68	84.2	81.7	0.999	135.7	<0.001	180.1	<0.001

The reference locations are listed in the first column (in brackets the distance in km from Kőszeg). The correlation coefficients (c.c.) between observational Kőszeg series and each reference station were significant for $p < 0.001$ (not shown). The differences of measured accumulated GDD between Kőszeg and reference datasets (1875–2009) were compared with those calculated for the pre-1875 period, between Kőszeg estimates (according to three different earliness hypotheses) and available measurements at the reference sites. The *p* values next to the estimated differences are the output of Wilcoxon rank sum test, assessing significance of this comparison

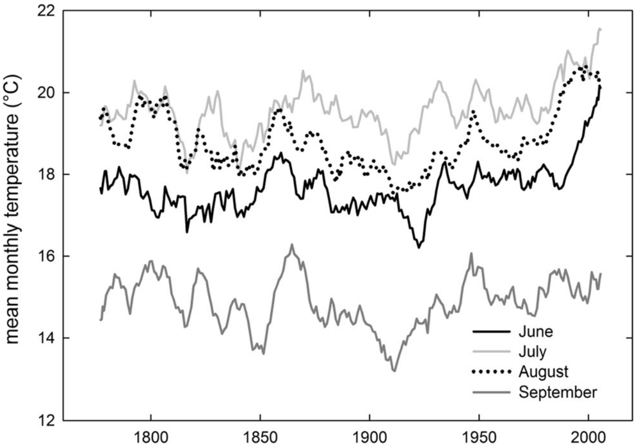

Fig. 8 Variation of the mean monthly temperature (10-year moving average) from 1775 to 2008 in Vienna (source: HistAlp project)

mean monthly temperatures (1775–2007) from June through September in the HistAlp Vienna dataset, it can be demonstrated that increasing trends did not occur until about the second decade of twentieth century.

Whatever the causes for varietal change, the crucial issue to our purposes is the identity or at least a reliable ecophysiological characterization of the ancient cultivars.

Kiss et al. (2010), from a survey of local historical documents, report the name of some cultivars known to be grown in the region during the eighteenth and nineteenth centuries. 'Zinfandel' and 'Furmint' are the most mentioned for both centuries. Neither of these is however compatible with the early development reported for the unknown cultivar of the 1875–1898 period. Robinson et al. (2012) reported 34 Hungarian autochthonous varieties, a number of which have comparable bud burst precocity with the unknown BOV type and are still cultivated: 'Ezerio', 'Juhfark', 'Keknyelu', 'Harsleveln', 'Menoir', and 'Leanyka'. This supports the hypotheses that pre-1899 shoots in the BOV refer to one or more unknown early-developing cultivars.

The hypotheses requires the complementary assumption that the observations between 1875 and 1898, the only period of the unknown parts which overlaps the measured temperature series, can be considered representative of the preceding years, or, stated in other words, the cultivars observed in this period are the same as in the previous years. While it is known that vineyards are replanted periodically, this was largely based on cuttings of the same variety, and there is no evidence to support any large scale replanting before 1875. This would favor the conservation of varieties across time, and makes it plausible to apply the models calibrated in 1875–1898 to the pre-1875 period. Great changes in viticulture are known to have happened only after the occurrence of phylloxera, which forced the adoption of grafted vines and of new varieties. Information that supports our thesis was found in the *Bollettino di Notizie Agrarie* (Bulletin of Agricultural News), published by the Italian Ministry of Agriculture, Industry and Commerce of Italy in 1884. This notice, entitled *Phylloxera in Hungary*, reported that the Hungarian commission of experts suggested the uprooting of only small, rather than extensive, areas, and did not encourage this practice. Based on this, it is legitimate to conclude that varietal renewal started later than our period of interest (1875–1898).

It cannot be excluded, though, that the earliness change could be only apparent, caused in fact by a change in shoot sampling criteria. In the first part of the period covered by the BOV, it might have been customary to harvest the absolute earliest shoots, thus making a systematic selective sampling of just the most early cultivar, and/or in particular sites with more favorable conditions (e.g., for aspects, elevation, soil type). Later, as more varieties started to be collected in more vineyards, the samples might have been chosen with more representative criteria.

Past temperatures estimation

Part of the reconstructed temperatures is based on interpreted verbal descriptions and on the assumption that years with no drawings correspond to the absence of shoots due to cold conditions. This raises the level of the uncertainty of estimates. Furthermore, BBCH-based estimates have an inherent low-end cutoff because the presence of closed buds, described or deduced from missing drawings, could not be univocally associated to a given temperature summation. Estimate consistency is therefore challenged in the coldest years of the period covered by our reconstruction.

From the literature available, the coldest spring in Europe during five centuries between 1500 and 2000 was in 1785

Table 6 Comparison of cold/warm extreme years reported in the study by Guiot et al. (2010) with reconstructed temperature series for Kőszeg

Cold years	Warm years
1770	1774
1799	1781
1805	1783
1812	1788
1816	1811
1817	1846
1838	
1843	
1845	

The years which agree with our reconstruction, i.e., those which represent a local maximum or minimum in our reconstructed time series, are underlined

(Xoplaki et al. 2005), which was affected by the effect of the disastrous Laki volcano eruption in Iceland during 1783–1784 (Thordarson and Self 2003) and coincided with the Dalton Minimum period of low solar activity and cooler global temperatures. The April mean temperature in 1785 is also the absolute coldest one in the Vienna and Prague-Clementinum datasets.

For 1784, the BOV reports only the bare annotation *there were no shoots on 24 April*, while from 1785 to 1787, no drawings were made at all. Given the contemporary documentation, it appears legitimate to postulate that missing data in BOV corresponded to absence of shoots, allowing at least the postulation that temperature summations were equal to or below the minimum threshold for bud burst.

Also, Maurer et al. (2009), using various documentary data from Vienna and Klosterneuburg, found that the coldest springs and summer starts occurred towards the end of the eighteenth century, in agreement with the reconstructed Kőszeg series. (Maurer et al. 2009), who reconstructed past climate from grape harvest dates in 15 Swiss localities, reported the occurrence of a cold period between the end of eighteenth century and the beginning of nineteenth.

Contrary to the Laki eruption, in the reconstructed series there is little evidence of the effects of the Tambora eruption, which caused the famous "year without a summer" in 1816. In fact, the effects on climate were evident in summer, but not in spring, when the BOV reports shoots with two to five leaves. In the Vienna dataset, March and April were respectively the 67th and the 79th coolest of the series. A likely consequence of the eruption could be the absence of drawings in 1817, which, as before, could be due to absence of shoots.

The following period, from 1860 to 1885, was characterized by decreasing temperatures.

Though not as pronounced as in late eighteenth century, cold conditions returned after the mid-nineteenth century. Rutishauer et al. (2007) report late springs in this period for the Swiss plateau, and (Maurer et al. 2009) report a colder period in the 1860–1870 decade.

A further important document reporting a long and gradual cooling during the nineteenth century is the ampelography treatise by Odart (1874), where concerns are expressed regarding the consequences for viticulture. Walkovsky (1998), who studied flowering in *Robinia pseudoacacia* in Hungary from 1851 to 1994, confirms that between 1851 and 1930, temperatures were lower than in the following period. The hottest springs occurred all in the twentieth century, namely in 1919, 1961, and 1989, with the GDD anomaly near or above 100 °C day^{-1}. Also of note is that periodic shifts of 100–200 °C day^{-1} were seen in both the reconstructed period (prior to 1875) and the observed period.

Other points of agreement between our reconstruction and other data can be found in a study by Guiot et al. (2010), who listed years which are documented as having been very warm or very cold in Europe. Those falling in the period covered in the BOV are listed in Table 6. Seven out of nine of the years reported in Guiot et al. (2010) as cold years are also years of local minima in our reconstruction series. Likewise, 5 out of 6 years documented as warm years are also local maxima in our estimations. The "warm/cold" classification of years according to our estimates takes into account only spring temperatures, but it could match classifications accounting for wider time intervals in years generally warmer or colder than normal, as those reported in literature. The satisfactory correspondence between our classification and that from other independent reconstructions further corroborates our estimations and the consistency of the pictorial information in the BOV.

Conclusions

A modeling analysis of the vine shoot-elongating phase based on BOV pictorial data revealed that a linear relationship exists between accumulated GDD and BBCH-coded development stages, which allowed past temperature reconstruction for spring in Kőszeg back to 1740.

The approach yielded consistent estimates under acceptance of the hypothesis that very early sprouting genotypes were cultivated before 1899, and that varietal homogeneity was preserved until that time.

According to the reconstruction, the period between 1740 and 1875 was characterized by colder springs than the baseline period 1960–1999, with a lower peak between 1784 and 1787.

Also, springs colder than the reference baseline generally prevailed over the nineteenth century, with a decreasing tendency starting from around the mid-century, until 1890.

While this study confirmed the difficulties of utilizing the large amount of pictorial information contained in the book, due to incomplete cultivar references and high heterogeneity, it nonetheless showed that with a few plausible assumptions, a consistent past temperature reconstruction can be advanced back to 1740 for this part of Europe, adding another piece of information to the collective work of historical climate reconstruction.

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