

Coincidence of temperature extremes and phenological events of grapevines

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ABSTRACT

A growing number of studies have highlighted the consequences of climate change on agriculture, including the impacts of climate extremes such as drought, heat waves and frost. The aim of this study was to assess the influence of temperature extremes on various phenological events of grapevine varieties in Southwest Switzerland (Leytron, Canton of Valais). We aimed to capture the occurrence of extreme events in specific years in various grapevine varieties and at different phenological phases to rank the varieties based on their sensitivity to temperature extremes and thus quantify their robustness. Phenological observations (1978–2018) of six *Vitis vinifera* varieties (Arvine, Chardonnay, Chasselas, Gamay, Pinot noir, and Syrah) were subjected to event coincidence analysis. Extreme events were defined as values in the uppermost or lowermost percentiles of the timing of the phenophases and daily temperatures within a 30-day window before the phenophase event occurred. Significantly more extreme temperature and phenological events occurred in Leytron between 2003 and 2017 than in the earlier years, with the years 2007, 2011, 2014 and 2017 being remarkable in terms of the number of extreme coincidence events. Moreover, bud development and flowering experienced significantly more extreme coincidence events than other phenophases; however, the occurrence rate of extreme coincidence events was independent of the phenophase. Based on the total number of extreme events, the varieties did not differ in their responses to temperature extremes. Therefore, event coincidence analysis is an appropriate tool to quantify the occurrence of extreme events. The occurrence of extreme temperature events clearly affected the advancement of the timings of phenological events in various grapevines. However, there were no varietal differences in terms of response to extreme temperatures; thus, additional research is warranted to outline the best adaptation measures.

KEYWORDS

phenological sensitivity, temperature stress, occurrence, Switzerland, coincidence

Supplementary data can be downloaded through: <https://oenone.eu/article/view/3187>

INTRODUCTION

The negative effects that climate change has on agriculture constitute a challenge, with the risk of extreme events being one of the key aspects of current climate research (Choudhary, 2015; FAO, 2016; IPCC, 2012; IPCC, 2018). The impact of climate change on viticulture has been extensively studied (Bernetti *et al.*, 2012; Fraga *et al.*, 2012; Mozell and Thach, 2014; Yzarra *et al.*, 2015), with studies specifically targeting viticultural suitability (Hannah *et al.*, 2013), grape and wine quality and production (de Orduña, 2010), irrigation strategies (Chaves *et al.*, 2010), tillage treatments (Fraga *et al.*, 2012) and grapevine growth stages in the face of changing climate (de Cortázar-Atauri *et al.*, 2017; Greer, 2013; Jones and Davis, 2000). Wine production regions worldwide have experienced changes in climate structure, resulting in shifts of the timing of phenological events in the grape varieties cultivated, changes in grape chemistry and wine quality, and increases in the incidence of insect-borne diseases and grape-ripening disorders, such as berry shrivel (Krasnow *et al.*, 2009; White *et al.*, 2006; Zufferey *et al.*, 2015a). According to grape producers cold and wet growing seasons, extreme heat conditions, rain during bloom and harvest delays are the most severe climate-related risks (Belliveau *et al.*, 2006).

Scientists have shown that the current climate changes have altered the frequency, intensity, spatial extent, duration and timing of extreme climate events (IPCC, 2012; IPCC, 2018). An extreme climate event is defined as ‘the occurrence of a value of a climate variable above (or below) a threshold value near the upper (or lower) end of the range of observed values of the variable’ (IPCC, 2012). There is some evidence that heat waves will occur more frequently (Meehl and Tebaldi, 2004) and drought will intensify in the 21st century during some seasons (mainly during summer) and in certain areas across Europe (Hov *et al.*, 2013). Extreme events, such as late spring frost (Leolini *et al.*, 2018) or extreme temperature and water stress, may significantly affect plant development (Gray and Brady, 2016; Hatfield and Prueger, 2015).

In cool regions, such as Switzerland, low temperatures often limit leaf and canopy photosynthesis and sugar production, although growth and sink activity of the fruit decrease to a greater extent than photosynthesis under low temperatures (Körner, 2003). Temperature and rainfall conditions are crucial before flowering.

Low temperatures (< 15 °C) can lead to poor fruit set due to excess flower abortion. Extreme frost and rainy events during the flowering period can lead to substantial yield losses (Keller and Koblet, 1995). Following fruit set (post flowering development), the rate and duration of cell division in the berry pericarp are controlled by the number of seeds in the berry, as well as by climatic conditions. Extreme temperatures (very cold or very warm) may inhibit cell division and expansion. Cell division is mostly under genetic control, whereas cell expansion is predominantly driven by environmental factors (Keller, 2015). Extreme heat events combined with water stress sharply decrease cell expansion and yield. Nonetheless, leaf photosynthesis can adapt to the prevailing temperature at a given time during the season, particularly after flowering, and this so-called modulative temperature adaptation (Larcher, 1995) may occur within a few days or, sometimes, hours. Possible modifications of substrate concentrations or RuBisCO activity and structural alterations of the bio-membranes may explain differences in adaptability to increasing temperatures across cultivars. For grapevines, local acclimation to the prevailing temperature conditions can mitigate the effects of extreme heat events during the ripening period (Zufferey *et al.*, 2000). However, a rise in temperature is often accompanied by an increase in canopy evapotranspiration, ultimately increasing the risk of water stress and physiological disorders, such as embolism events (*e.g.*, disruption of the hydraulic conductivity of the vessels) (Zufferey *et al.*, 2011), which may further inhibit plant photosynthesis and growth and reduce productivity (Dayer *et al.*, 2017).

To avoid such consequences and maintain the yield and quality of vineyard harvest, adaptation strategies (Mosedale *et al.*, 2016; van Leeuwen *et al.*, 2019a) are needed. Without these strategies, extreme heat is expected to have detrimental effects on vine physiology and yield, even though some varieties are more tolerant of extreme temperatures than others (Santos *et al.*, 2020).

In the Swiss Rhone catchment (Valais), permanent crop cultivation (orchards and vineyards) and livestock production are the most important agro-economic activities. Under the predicted climate change scenarios, the adverse effects of extreme heat events on Swiss vineyards are expected to become a threat in the upcoming decades (Fuhrer *et al.*, 2014). Although there are some data on the increasing risk of spring frost

damage in grapevines due to climate change in the Swiss Rhone (Meier *et al.*, 2018), there remains a knowledge gap regarding the risk of extreme temperature events in grapevine plantations in this region.

To this end, the aim of this study was to address the following questions: (1) can the effects of extreme temperature events on grapevine phenophases be captured? (2) which phenophases are the most sensitive to extreme temperature events? and (3) which grape varieties are the most robust (or least sensitive) under extreme temperatures? The observed patterns may offer novel insights to aid wine producers in decision-making on vineyard management in the face of climate change.

MATERIALS AND METHODS

1. Study area and phenological data

Data from six grapevine varieties (*Vitis vinifera* L. Arvine, Chardonnay, Chasselas, Gamay, Pinot noir and Syrah) cultivated at the experimental vineyard of Agroscope in Leytron (LEY; Canton of Valais, 46°10' N, 7°12' E; 485 m a.s.l.; Figure 1) were analysed.

The Canton of Valais is one of the driest regions of Switzerland, with approximately 550 mm of mean annual precipitation in its central Rhône valley. Almost 30 % of the area of Leytron is used for agricultural purposes.

Experts from the Plant Sciences Institute collected phenological observations for 41 years (1978–2018) at Agroscope in Changins (Figure 1) and observations at the vineyard of Agroscope are still ongoing. The complete list of phenophases is presented in Supplementary Information (Table S1). Phenological observations were obtained from adult vines (30 plants per variety) with identical canopy and soil management. Vines were planted in the Guyot pruning system (vertical shoot position trellis system) at a planting density of 5,500 vines/ha. The experimental site (5 ha) in LEY has very stony soil (gravelly, > 60 % large elements, stones, blocks and gravel) and deep soil (vine root depth, > 2.5 m), with an estimated water-holding capacity of 150 mm. The number of observations varied among years and phenophases (SI, Figure S1). All 36 studied phenophases were defined according to the Biologische Bundesanstalt Bundessortenamt und Chemische Industrie (BBCH) scale (Bloesch and Viret, 2008; Lorenz *et al.*, 1994; Meier, 1997).

2. Meteorological data

Datasets at the study site in Leytron (LEY) were required in order to determine the coincidence between the occurrence of extreme temperature events and the selected phenological phases of *V. vinifera*, daily minimum, mean and maximum temperature.

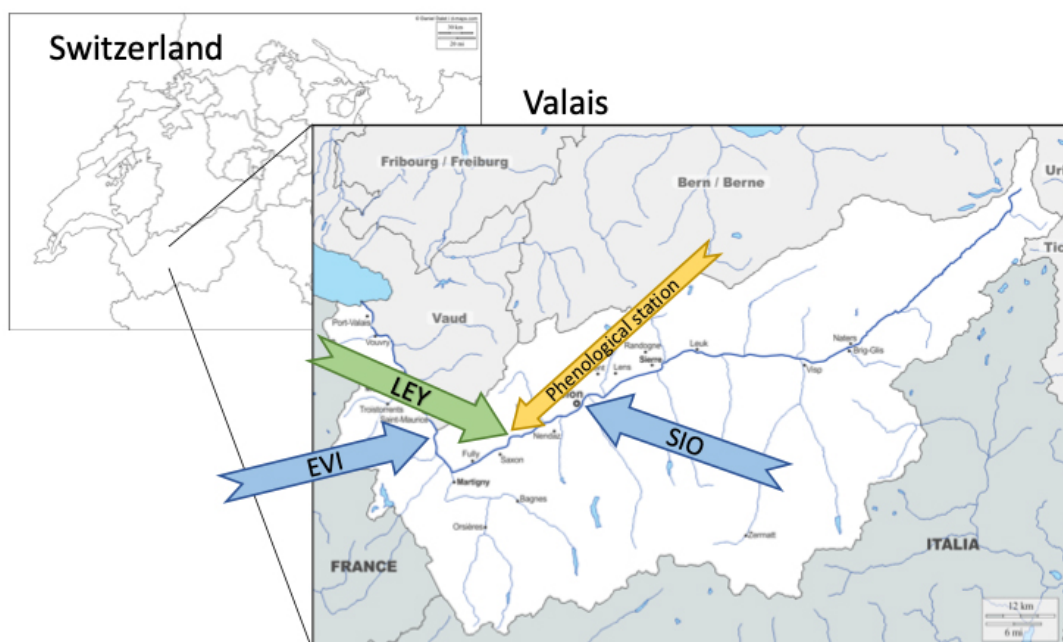


FIGURE 1. Map showing the location of the study site and data sources in the Canton of Valais, Switzerland. Phenological data were collected from a vineyard located in Leytron (LEY); meteorological data were gathered from LEY, Sion (SIO) and Evionnaz (EVI).

Temperature at 2 m above ground level (a.g.l.) has been recorded by the Agrometeo Weather Station within the vineyard of interest since 2003 (available at <http://www.agrometeo.ch/de/meteorology/datas>), and these data were used in the present analysis. Additional temperature data from MeteoSwiss (<https://gate.meteoswiss.ch/idaweb/>) were also collected from the neighbouring weather stations at Sion (SIO) and Evionnaz (EVI), where daily temperature measurements at 2 m a.g.l. have been obtained since 1976 and 1993 respectively. Finally, the daily minimum, mean and maximum temperature values in LEY were estimated using single- and bivariate linear regression models ($LEY \sim SIO$ and $LEY \sim SIO + EVI$) for 1978–1992 and 1993–2002 respectively. Agrometeorological observations for the years 2003–2018 were used.

As temperatures at SIO and EVI were highly correlated, observations at the latter station were partialled out from the linear regression ($EVI \sim SIO$). Finally, the remaining daily residuals were subjected to bivariate linear regression ($LEY \sim SIO + rEVI$, where $rEVI = EVI - \widehat{EVI}$, with \widehat{EVI} being the predicted temperature in Evionnaz).

For temperature estimation, overlapping observations were used from 2003 to 2014. A random sample of 60 % of these overlapping observations was used for calibration of the linear regression models, and the remaining 40 % was used to evaluate temperature estimation based on root mean square error (RMSE) and Nash-Sutcliffe efficiency [NSE; (Nash and Sutcliffe, 1970)] index. The RMSE values were between 0.54 and 1.00 °C, and the NSE values were between 0.98 and 0.99, indicating a satisfactory temperature reconstruction for LEY (Table 1). The average temperature time series of the whole period (1978–2018) is shown in SI, Figure S2.

TABLE 1. Root mean square error (RMSE) and Nash–Sutcliffe efficiency (NSE) index for the single and bivariate linear regression models of daily minimum, mean, and maximum temperature values in Leytron (LEY).

Measure of accuracy	Variable	LEY ~ SIO (°C)	LEY ~ SIO + rEVI (°C)
RMSE	Daily minimum temperature	1.0003	0.08462
NSE	Daily minimum temperature	0.9809	0.9864
RMSE	Daily mean temperature	0.6383	0.5350
NSE	Daily mean temperature	0.9938	0.9956
RMSE	Daily maximum temperature	0.9117	0.8100
NSE	Daily maximum temperature	0.9899	0.9920

The corresponding temperatures in Sion (SIO) and Evionnaz (EVI) were used as explanatory variables, with the latter being partialled-out and only the residual ($rEVI$) used.

3. Data analysis

To characterise various phenophases (Bloesch and Viret, 2008), phenological trends were calculated for each grape variety (Figure 2). The trend lines and the corresponding confidence interval were estimated based on a generalised additive model (Hastie and Tibshirani, 1990) with a smoothing function using thin plate regression splines (Wood, 2003). As an example, exploratory analysis for Syrah between temperature and day of the leaf unfolding phenophase were made (Figure 3).

3.1 Quantifying the occurrence of extreme events

Event coincidence analysis was used (Donges *et al.*, 2011; Donges *et al.*, 2016) to identify whether the timing of extremely early or late phenological events was in accordance with the periods of extremely low or high daily temperature conditions. To achieve this, first, the occurrence of extreme events was quantified, and then the coincidence between the extreme events captured in the temperature and phenological data was identified (Figure 4C), as described by Siegmund *et al.* (2016) with minor modifications (see Supplementary Information for details). We compared the Siegmund method to two other methods (quantile and robust covariance methods) to determine its novelty and assess what type of additional new information it can provide. Of note, mean temperature in this study indicates the arithmetic mean of the mean temperature values in a specific time window before the phenological event occurred (from 33 days before until 3 days before the occurrence of the phenological event).

Using the quantile method, the (0.1 and 0.9) quantiles of the mean temperature and the quantile of the phenological data were calculated

and extreme values were identified (indicated within the lower right and top left corner of Figure 4A). This approach is an over-simplification of the Siegmund method, because all temperature values are no longer evaluated on a daily basis and are instead summarised within a given time window (Figures 3 and 4).

Alternatively, the robust covariance estimation method was applied to identify extreme values. We estimated the bivariate robust covariance (minimum covariance determinant; Rousseeuw, 1999) of the mean temperature and day-of-year (doy) values of the phenophase in each year to detect atypical observations (Figure 4B). Outliers in the 0.8 quantiles of the chi-square distribution with 36 degrees of freedom (1978–2018, 36 years), which appear in the lower quarter of the ellipse (the year with mean temperature higher than the median of temperature values of all years, but do year lower than the median do year) indicate early extremes. Meanwhile, observations in the upper left corner of Figure 4B indicate (if any) late extremes.

3.2. Estimation of years with high coincidence of extreme events

An overview of the extreme coincidences in Syrah at each studied year is visualised in Figure 5. Corresponding figures for all other studied varieties are available in Supplementary Information (SI, Figures S3 - S7). One-sided Poisson test was applied to identify the years with significantly more extreme events than others. For this test, the coincident extreme events of all phenological phases were counted for each grapevine variety and each year and then divided by the total number of phenological phases for each grapevine variety within a year. Our null hypothesis was that the rate of extreme events is 0.2 (20 %) and the alternative hypothesis was that this rate is higher than 0.2 (20 %). The rate is based on the definition of quantiles (top and bottom 10 %). Based on the upper confidence interval obtained from the Poisson test, we were able to examine whether the occurrence rate of an extreme event in a given year was significantly higher than 0.2 (indicated by black or grey bars in Figure 7). The higher the rate, the more the extreme event at a given phenophase in a given year.

3.3. Estimation of the occurrence rate per phenophase

Both the number and rate of occurrence of extreme events per phenophase (Bloesch and Viret, 2008)

were estimated to determine the phenophase that was the most susceptible to temperature extremes (Table 3). The rate of extreme event occurrence was defined as the number of coinciding extreme events per phenophase divided by the total number of coinciding extreme events. The following phenophases were investigated: 0: bud development (BBCH 0-9), 1: leaf development (BBCH 10-16), 5: inflorescence emergence (BBCH 53-59), 6: flowering (BBCH 61-69), 7: fruit development (BBCH 71-79) and 8: ripening of berries (BBCH 81-89). The codes of phenophases follow the BBCH classification (Bloesch and Viret, 2008; see SI, Table S1 for more details). Pairwise proportional tests (Newcombe, 1998) were applied to test for differences in occurrence of coincidence rates between growth stages. p-values were corrected for multiple testing with method Holm (Holm, 1979). Our null hypothesis (H_0) was that the rate of extreme coincidences is 20 %, and if the rate is higher than this value, H_0 is rejected, indicating significance.

3.4. Calculation of the sensitivity of the grapevine

For demonstrative purposes, the coincidences of extreme phenological and temperature events of six grapevine varieties in one of the warmest years on record (2017) and in a usual year (1999; with only a few extreme coincidence events per year confirmed by Figure S3-S7) are shown in Figures 6A and 6B respectively. To evaluate the sensitivity of grapevine varieties to extreme temperature events, the total number and rate of occurrence of extreme events were calculated for each variety. The occurrence rate was calculated by factoring in the number of years in which observations were made. Our hypothesis was that the fewer the extreme events in a time series, the more robust the variety is to extreme temperatures. A value of 0 indicated a very robust variety, meaning that it is robust against extreme heat, as no extreme phenological event coincided with an extreme temperature event in its dataset. Meanwhile, a value of 1 indicated a very sensitive variety. Extreme events of ‘doy only’ (extreme phenological event without coincidence with an extreme temperature event) were not considered in this analysis. To determine differences across varieties based on the occurrence rate, we conducted Poisson exact test for two samples (Fay, 2010).

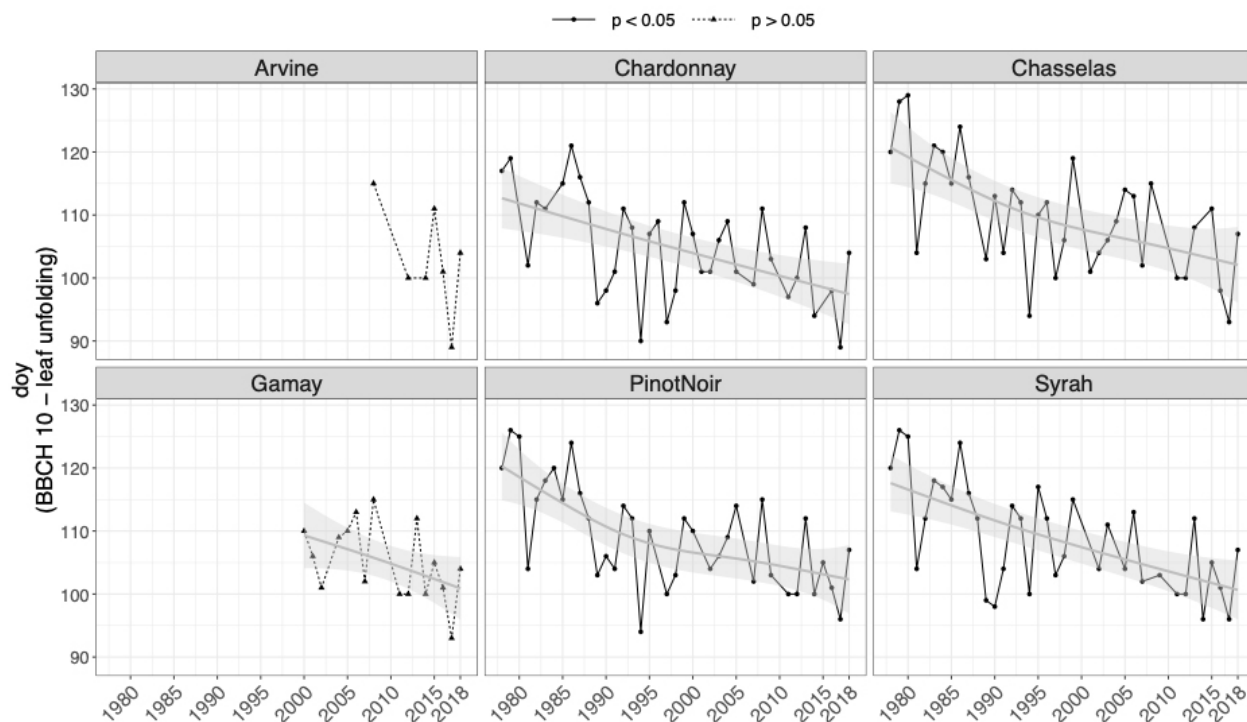


FIGURE 2. Annual variations (1978–2018) in the timing of the leaf unfolding (BBCH 10; Bloesch and Viret, 2008) phenophase in Leytron, Switzerland, for different grapevine varieties. Abbreviations: doy: day of the year.

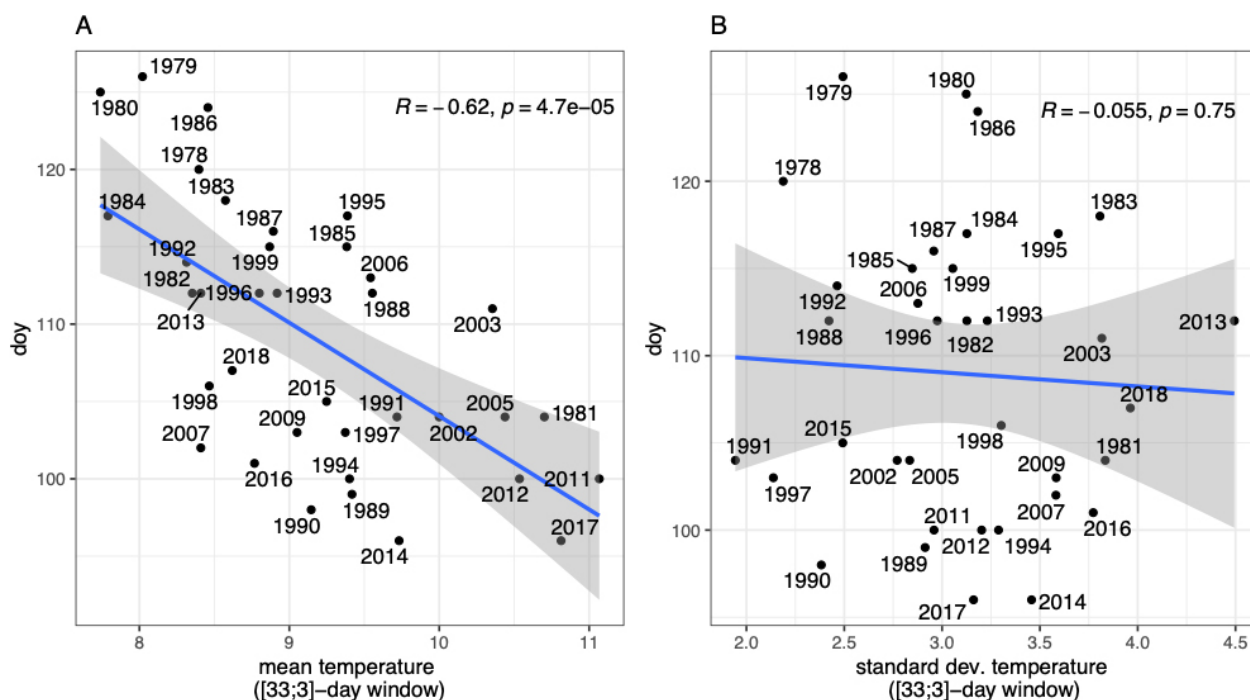


FIGURE 3. Exploratory analysis for Syrah as an example. Day of the year (doy) of the leaf unfolding phenophase (BBCH 10; Bloesch and Viret, 2008) in response to mean temperature (A) and standard deviation of temperature values from 33 days before until 3 days before the event in each year (B). Blue line represents the ordinary least squares (OLS) regression line and the grey shaded areas correspond to the confidence intervals.

RESULTS

1. Phenological characteristics

This section provides an overview of the phenological trends found in our study (Figure 2), specifically in response to mean temperature (Figure 3). An example is shown in Figure 2, demonstrating that the timing of leaf unfolding (BBCH 10; Bloesch and Viret, 2008) has become earlier. We found that almost all studied phenophases showed advancing trends in all varieties within the study period (results not shown).

We found a relatively strong negative linear correlation (Pearson correlation, $r = -0.62$) between day of the phenophase (here leaf unfolding, BBCH 10; Bloesch and Viret, 2008) and mean temperature within the given time window (Figure 3A). For instance, in 2017, very early leaf unfolding can be observed, because the average temperature before the event was very high. Interestingly, however, there is no correlation ($r = -0.05$) between the temperature values within this time window and the leaf unfolding event, indicating that fluctuations in temperature hardly influenced the timing of leaf unfolding (Figure 3B). Similarly, there are strong correlations between mean temperatures and phenological events for other grape varieties (results not shown), thus supporting our speculations.

2. Occurrence of extreme events

2.1. Occurrence of extreme events in specific years

In this section, the results of the comparison of various methods applied to identify the coincidence of extreme events in specific years are given. As an example, the results of the analysis of the leaf unfolding data (BBCH 10) for Syrah and mean temperatures within the given time window (section Data analysis) using various methods are summarised.

The quantile method (Figure 4A) identified fewer extreme coincidences than the other methods. It captured only 2017 as a year of extremely early coincidence events based on the mean temperature and timing of leaf unfolding; however, it classified 1979 and 1980 as the years of late coincidence events in which cold temperatures delayed leaf unfolding in Syrah.

The robust covariance estimation method (Figure 4B) detected only 2011 as an unusual year.

In this year, daily mean temperatures before leaf unfolding were high, but leaf unfolding occurred relatively late. Therefore, this method is useful for outlier detection - to assess whether the relationship between temperature and phenological events is unusual - as it is suitable for event coincidence analysis

The modified Siegmund method (Figure 4C) identified the most extreme coincidence events (4 early and 4 late extreme coincidences), due to it being more sophisticated and analytical than the other two methods (see Supplementary Information for details).

2.2. Occurrence of extreme coincidence events per phenophase

In this section, we provide an overview of the occurrence of extreme coincidence events per phenophase in order to identify the stages that are more susceptible to extreme temperatures than others. We identified more extreme coincidence events with the Siegmund method than with the other two methods together. Pairwise proportional tests between the relative occurrence of extremes between growth stages showed significant differences between bud development and inflorescence merge (corrected p-value: 0.049) and bud development and ripening of berries (corrected p-value: 0.023); for example (see also Table 2), 55/171 (relative occurrence of coincidence extremes in bud development growth stage) was significantly larger than $99/478$ (related to inflorescence merge), even after p-values correction for multiple testing. The rate of occurrence of extreme coincidence events was almost equal for all the other phenophases in the Siegmund method. The number of extreme coincidence events identified by the quantile method varied across different phenophases; for example, it did not detect ample extreme coincidences at the bud development stage. The robust covariance estimation method revealed a very similar rate of occurrences amongst phenophases; however, it detected almost 50 % fewer coincidence events than the Siegmund method (Table 2).

The years 2007, 2011, 2014 and 2017 were remarkable (Figure 5) in terms of the number of extreme coincidence events during many phenophases. Figure 5 provides an overview of the extreme coincidences (vertical bar) in Syrah during each studied year. Corresponding figures for all other studied varieties are available in Supplementary Information (Figures S3-S7).

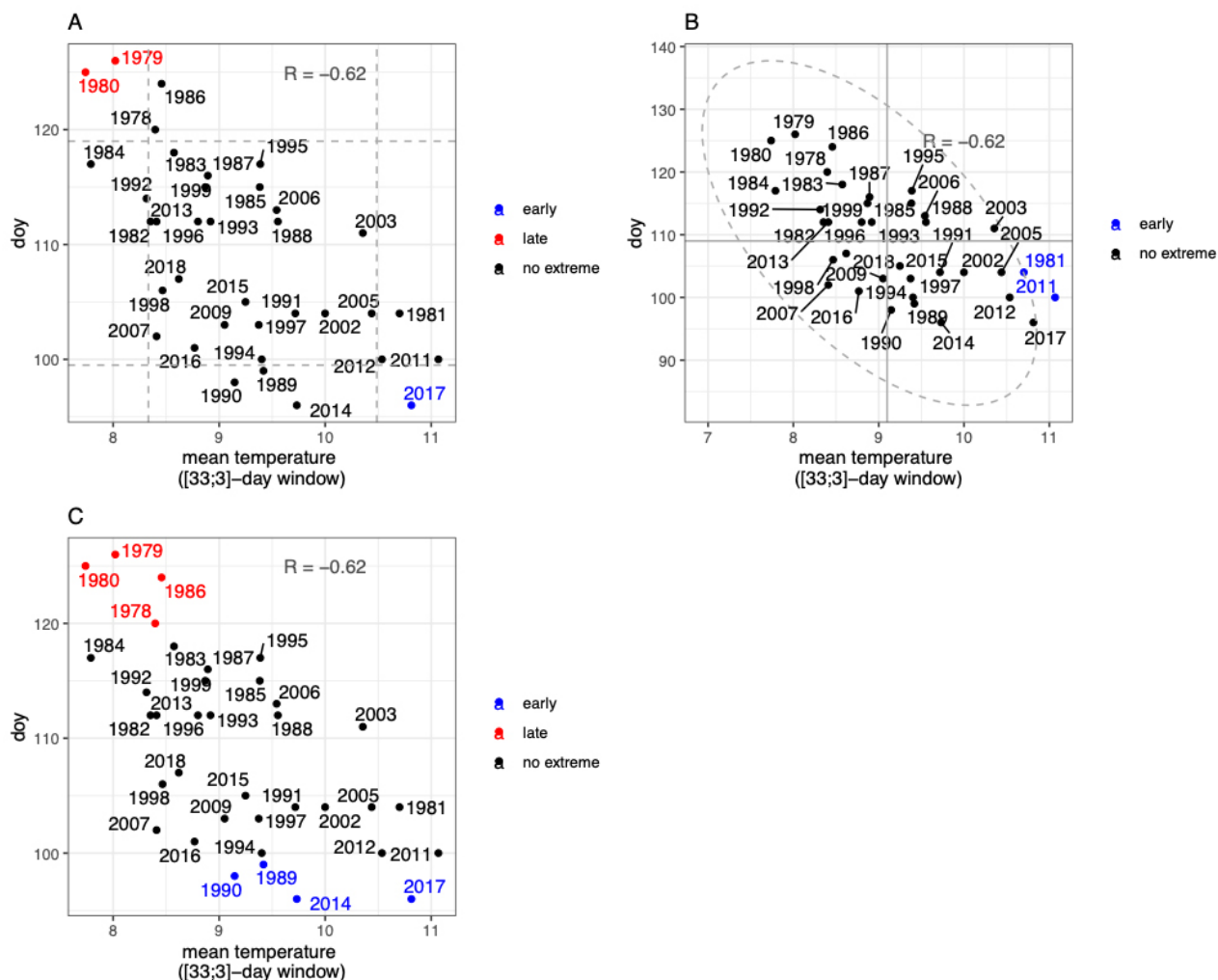


FIGURE 4. Comparison of results of the three methods [quantile, robust covariance estimation and Siegmund methods (Siegmund *et al.*, 2016)] to identify extreme (early or late) events.

As an example, the results of the analysis of the leaf unfolding data for Syrah are shown. Quantile method (Figure 4A): the (0.1 and 0.9) quantiles are indicated in grey lines for the phenological (horizontal dashed lines) and climatological (vertical dashed lines) time series. Extremely early events are located in the lower right-hand corner, whilst extremely late events are located in the top left-hand corner. Robust covariance estimation (Figure 4B): any outlier occurring outside the 0.8 tolerance ellipse is considered an extreme event. Siegmund method (Figure 4C): coincidence between the extreme (early or late) events is captured based on the method described by Siegmund *et al.* (2016) with some modifications.

TABLE 2. Number of extreme coincidence events and rate of occurrence of extreme coincidence events per phenophase [according to the BBCH scale (Bloesch and Viret, 2008)], estimated using various methods [quantile, robust covariance estimation and Siegmund methods (Siegmund *et al.*, 2016)].

	Bud development	Leaf development	Inflorescence emergence	Flowering	Fruit development	Ripening of berries	Total
growth stage	0-9	10-14	53-57	61-69	71-77	81-89	0-89
count	171	503	478	550	393	629	2724
extremes (Siegmund)	55	110	99	139	88	128	619
extremes (Quantile)	8	34	11	32	15	50	150
extremes (RobCov)	28	66	55	58	54	79	340
occurrence (Siegmund)	22.53	15.32	14.51	17.7	15.69	14.25	100
occurrence (Quantile)	14.94	21.58	7.35	18.57	12.19	25.38	100
occurrence (RobCov)	21.03	16.86	14.78	13.55	17.65	16.13	100

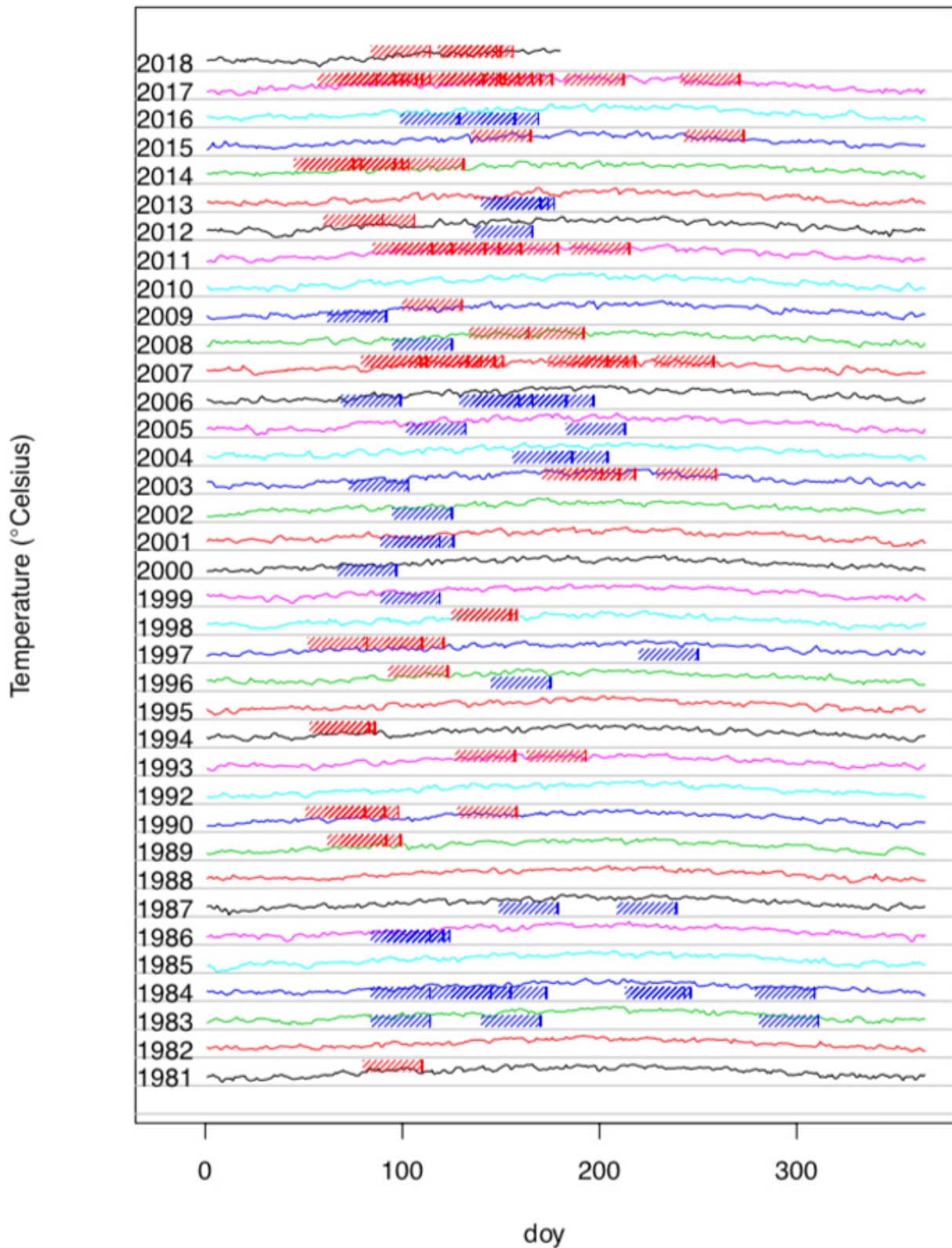


FIGURE 5. Coincidences of extreme phenological and temperature events in Syrah.

The polygon lines indicate the daily mean temperatures of the corresponding years. The coloured areas indicate extreme coincidences [according to Siegmund *et al.*, (2016)] within the time window of the year before the occurrence of the phenological event. The colour of the bars corresponds to the direction of the extreme phenological shift (red bars: earlier doys; blue bars: later doys). The number of bars within the colour-shaded area corresponds to the number of extreme coincidence events. All phenological events considered in the analysis are listed in SI in Table S1.

2.3. Occurrence of extreme coincidence events per grapevine variety

In 2017, all grapevine varieties exhibited extreme phenological responses to temperatures throughout the year (Figure 6A). The most extreme coincidence events appeared from April to August (doy: 95–195), when the phenological events of all varieties were shifted to an earlier doym (red areas in Figure 6A). For comparison, the same Figure was generated for the year 1999 (Figure 6B), which demonstrates the distribution of data of a ‘usual’ year.

Only some extreme coincidence events were detected in 1999, when the phenological events of the plants were shifted to a later doym (blue areas in Figure 6B).

No significant differences were observed in terms of the occurrence of extreme coincidence events between the grapevine varieties studied. Based on our results (Table 3, Poisson exact test for two samples), the tested varieties were similarly affected by temperature extremes in the Cantone of Valais, and it is therefore not possible to state whether a specific variety is more robust.

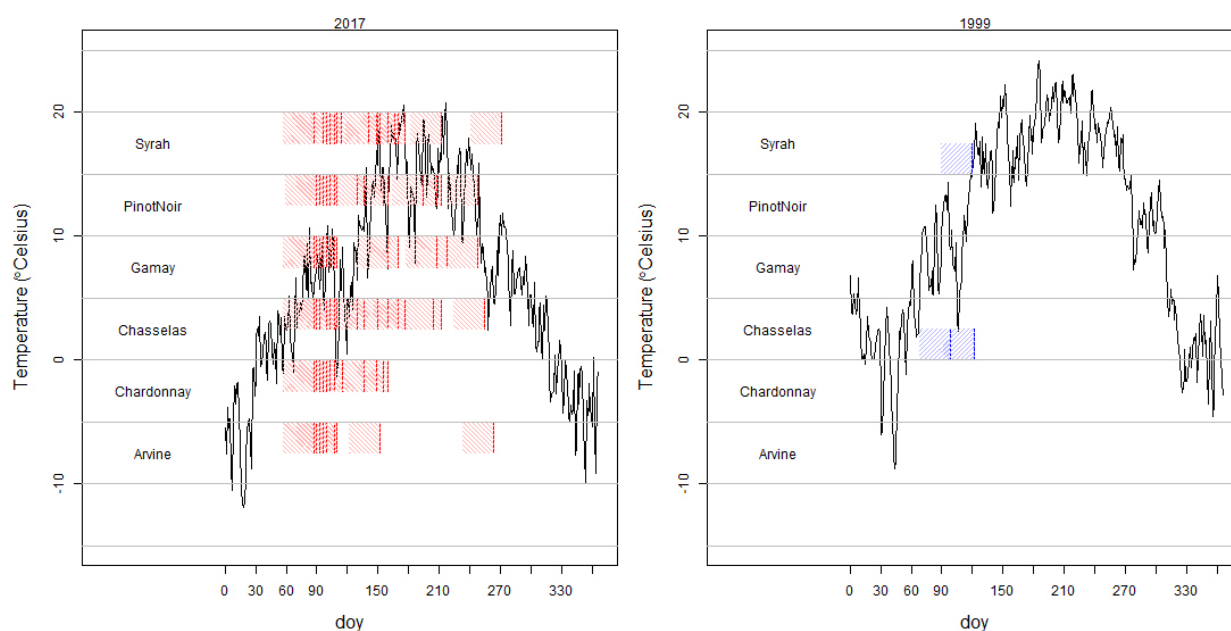


FIGURE 6. Example of coincidences of extreme phenological and temperature events of six grapevine varieties in (A) 2017, one of the warmest years on record and in (B) 1999, a usual year.

The coloured areas indicate extreme coincidences (according to Siegmund *et al.*, 2016) within the time window of the year before the occurrence of the phenological event. The colour of the bars corresponds to the direction of the extreme phenological shift (red bars: earlier doym; blue bars: later doym). The number of bars within the coloured area corresponds to the number of extreme coincidence events. All phenological events considered in the analysis are listed in Supplementary Information (Table S1).

TABLE 3. Occurrence of extreme coincidence events (1978–2018) affecting grapevines in Leytron.

	Arvine	Chardonnay	Chasselas	Gamay	Pinot noir	Syrah
no. of years	11	41	41	19	41	41
no. of observations	171	573	554	315	567	544
no. of extremes (Siegmund)	54	125	125	81	115	119
no. of extremes (Quantile)	10	37	27	14	26	36
no. of extremes (RobCov)	22	70	65	54	63	66
occurrence rate (Siegmund)	4.91	3.05	3.05	4.26	2.8	2.9
occurrence rate (Quantile)	0.91	0.9	0.66	0.74	0.63	0.88
occurrence rate (RobCov)	2	1.71	1.59	2.84	1.54	1.61

The number of extreme coincidences per year is the rate of occurrence of extreme coincidence events. The higher the sensitivity of a variety, the higher the occurrence rate; conversely, the lower the value, the more robust the variety. The value 0 indicates a very robust variety, meaning that it can withstand extreme heat, as no extreme phenological event coincided with an extreme temperature event in its dataset.

Pairwise proportional tests showed only significant differences between Arvine and Pinot noir, although this result should be treated with caution as only 11 years were observed for Arvine. When only the last 11 years of all wine varieties are analysed, there are (also) no significant differences between the coincidence rates of these two wine varieties (rate Arvine 11/171 *versus* Pinot noir 12/199). The results of the Poisson test show the years when the grapevines experienced a significant rate of extreme coincidences (black bars in Figure 7). Higher rates correspond to more phenophases that coincided with the extreme temperature events in a given year in a given grapevine variety.

Consistent with our expectations, significantly more coincident extreme events (in both phenological and temperature datasets) occurred after 2000 (Figure 7). Similar graphs are available for the quantile and robust covariance estimation methods in Supplementary Information (Figures S8 and S9).

DISCUSSION

The results in Figure 2 show that, on average, flowering takes place earlier and earlier. When comparing the respective temperatures of a given year before the flowering event, it is possible to observe an increase in temperature before the flowering event over the years (see, for example, Figure 3); this is obviously negatively correlated with the day of the year in which the phenological events took place; which is not surprising and is consistent with many studies. Climate-induced phenological shifts have been observed across Switzerland (Bigler and Bugmann, 2018). Scientists have shown that the current climate changes have led to changes in the frequency, intensity, spatial extent, duration and timing of extreme climate events throughout the world (IPCC, 2012; IPCC, 2018). Data from Austria, France (Chuine *et al.*, 2004; Duchêne *et al.*, 2010; Maurer *et al.*, 2011), Germany (Menzel, 2005) and the Swiss Alps (Büntgen *et al.*, 2006) have confirmed that the year 2003 was an unprecedented extreme year (García-Herrera *et al.*, 2010).

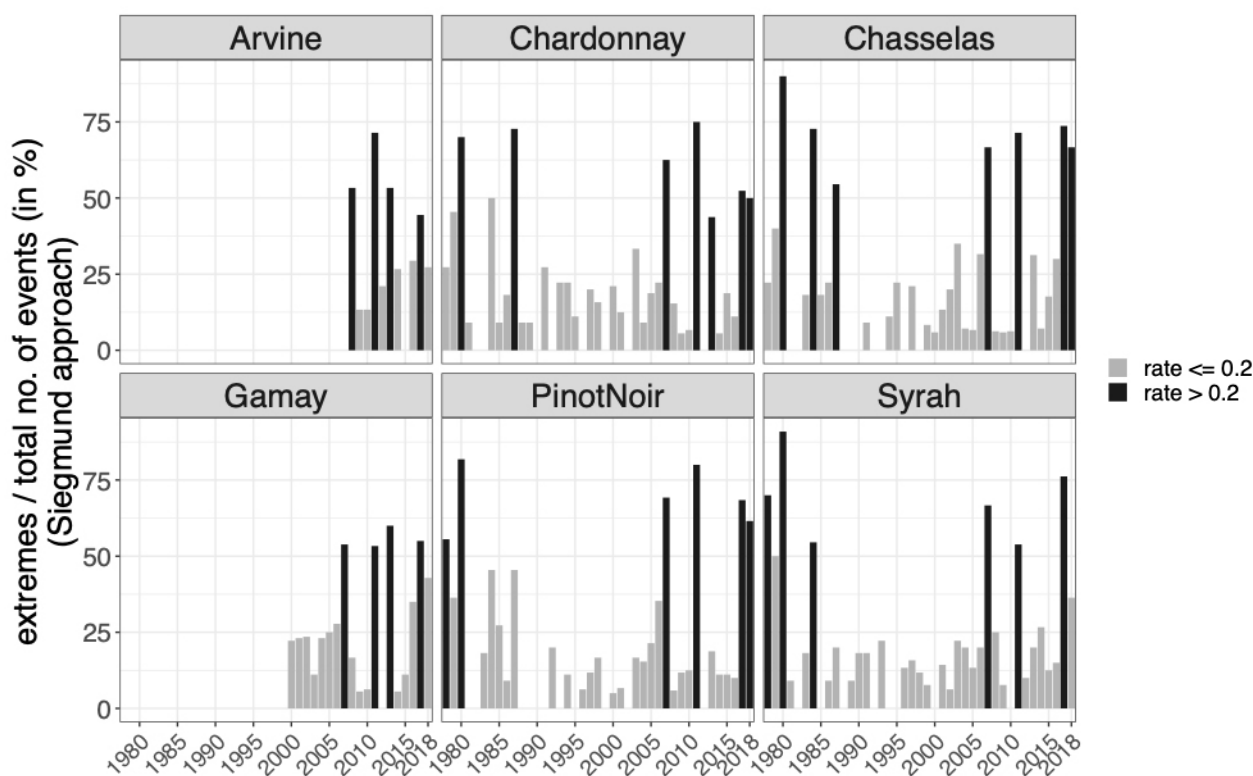


FIGURE 7. Distribution of the number of extreme phenological events (all 36 BBCH phenophases) in the studied grapevine varieties over the study period (1978–2018) in Leytron.

The height of the bars represents the number of extreme coincidence events. Black bars indicate greater than 20 % rate of extreme events ($p = 0.05$); grey bars indicate non-significant years. Higher rates correspond to more phenophases that coincided with the extreme temperature events in a given year in a given grapevine variety. Data at the beginning of the study period are missing for Arvine (1978–2007) and Gamay (1978–1999).

Many parts of Europe experienced record-breaking temperatures during July 2006, exceeding the values recorded in 2003 (Dankers and Hiederer, 2008). Furthermore, the winter season of 2006–2007 was estimated to be the warmest in the previous 500 years (Luterbacher *et al.*, 2007). These extreme years are also confirmed by meteorological data set from Sion (SIO) and Evionnaz (both in Switzerland) that we used for this study.

Generally, temperature is a key factor affecting plant development (Went, 1953). The ultimate impact of temperature stress on yield or reproductive fitness depends on the developmental stage at which the high temperature stress occurs (Gray and Brady, 2016; Hatfield and Prueger, 2015), as well as on the variety (Martínez-Lüscher *et al.*, 2016). Water stress also increases the vine's susceptibility to heat stress and drought during the bloom period is especially detrimental to fruit set, if it coincides with a heat period (Srinivasan and Mullins, 1981). The upper temperature limit for maximum yield formation in grapevines seems to be at 35 °C (Keller, 2015). Higher temperatures (> 35 °C) can produce a so-called heat-shock and protein deformation in berries with sunburn symptoms as an expression of oxidative damage from a combination of high light intensity and high temperature (Iba, 2002). The acclimation to low temperatures (< 15°C) - known as chilling acclimation - during the season leads to higher leaf photosynthetic rates and water use efficiency at lower temperatures, because of a downward shift in the optimum temperature for photosynthesis (Zufferey *et al.*, 2000). Reproductive development is more vulnerable to chilling stress during the pre-flowering stage (Keller, 2015), because fruit sink activity is more sensitive to temperature and carbon shortage at this time than shoot sink activity. Previous studies mainly showed correlations between climatic variables (such as temperature) and flowering times, mostly by linear correlation or linear regression (*e.g.*, Menzel, 2005) or model non-linear responses to temperature (*e.g.*, de Cortázar-Atauri *et al.*, 2010). An exception is the study from Siegmund *et al.* (2016), who first used appropriate techniques to identify periods prior to the growing season, where extreme temperature events are statistically related to extreme flowering dates. In this study, we carried out an event coincident analysis (modified from Siegmund *et al.*, 2016) to identify the way in which extreme temperature events control the timing of grapevine phenophases.

Furthermore, we applied two other methods (quantile and robust covariance estimation) to compare the results of the modified Siegmund method and prove its novelty.

Using the phenological and temperature datasets, we identified the years when extreme events in both datasets coincided with one another. We showed that most of these coincidental events occurred after 2000 (mainly in 2007, 2011, 2014 and 2017; see Figures 4 and 7), which is the warmest decade on record since the beginning of the modern meteorological records (WMO, 2013; Arguez *et al.*, 2020).

The analysis and results confirmed that our modified Siegmund method is more sophisticated than the other two methods, bringing added value to the detection of extreme coincidence events, which provides us new knowledge about the extreme events in the studied Swiss vineyard. By using this method, we discovered that bud development and flowering experienced more extreme coincidence events than the other phenophases and that bud development has significantly more extreme coincidence events than inflorescence merge and ripening of berries. In particular, the much larger influence of temperature on bud development compared to other phenophases has also been shown by other studies, even if they focused on other types of wine from other regions (Malheiro *et al.*, 2013). Lethal freeze injury to buds is decisive during winter and spring in terms of potential yield. Low temperatures lead to cold acclimation during winter. Nevertheless, warm episodes during the acclimation period induce rapid de-acclimation, causing problems when a freezing event follows a mild winter, for example. Osmotic adjustment in buds, especially the adjustment of osmotically active sugars (sucrose, glucose and fructose), is essential for good acclimation, because it reduces cell dehydration and inhibits the nucleation and growth of ice crystals in bud cells (Keller, 2015). Deficient C- and N-reserves in permanent grapevine organs and a sudden increase in temperature in early spring can lead to early budbreak, increasing the risk of bud freeze and loss of fruit formation (Zufferey *et al.*, 2015b).

We did not find any significant differences in the sensitivity of the tested varieties based on the occurrence rate of extreme coincidence events. Thus, we could only rank them based on the total number of extreme coincidence events they experienced during 1978–2018. Disregarding the two wine varieties Arvine

and Gamay, from which we had less data, Chasselas and Chardonnay experienced the most extreme events (Robinson *et al.*, 2012; Töpfer *et al.*, 2009); these varieties can therefore be ranked as the most sensitive of the studied ones, which is in line with conclusions drawn by Robinson *et al.* (2012) and Töpfer *et al.* (2009). Zufferey *et al.* (2000) reported that photosynthetic rate was observed to increase with increasing temperature for Chasselas, compared with other European cultivars such as Riesling. Even when modulative temperature adaptation occurred (Larcher, 1995), with increasing water scarcity and extreme temperatures hydraulic failure was observed in the leaf and petiole vessels (xylem tissues) of Chasselas (Zufferey *et al.*, 2011). It is also known that for Pinot noir, the climatic niche is narrow, and the average growing-season temperature for this variety is relatively low (Spring *et al.*, 2010). Early-ripening varieties such as Chasselas, Pinot noir and Chardonnay could become more widespread globally, if they were to be cultivated in new, more poleward regions (such as Canada, northern Europe and Tasmania; Morales-Castilla *et al.*, 2020).

The time series for Arvine and Gamay were too short, and when all the wine varieties were broken down to this short time, our results were not significant. From literature, it is known that Gamay is grown in cool-climate regions such as Canada and Switzerland (Robinson *et al.*, 2012). While the white varieties (Chardonnay, Chasselas and Arvine) are poorly suited to the dry conditions (Zufferey *et al.* 2020), the cultivar Arvine is particularly sensitive to temperature increase and water scarcity events, thus influencing its aromatic compounds. When heat-susceptible cultivars, such as Arvine, are grown in warm climates or in hot growing seasons with intense solar radiation, they often develop poor aromatic compounds in berries and have a negative impact on wine quality (Zufferey *et al.*, 2020). More data on Gamay and Arvine would be necessary to prove these statements using our methodology. Syrah (and Pinot noir) were the least sensitive of all the wine varieties examined in this study (see Table 3 and Figure 7). Late-ripening varieties, such as Syrah, Grenache and Mourvedre, are projected to become much more widespread in current global winegrowing regions if temperatures rise by 2 °C (Morales-Castilla *et al.*, 2020).

Several attempts have been made to evaluate drought tolerance and to rank grape varieties (Parker *et al.*, 2011; Parker *et al.*, 2013), in order

to help select the variety best adapted to climate change. However, these data are not yet available for all varieties. Wine growers could therefore maintain their income by replacing the grapevines they cultivate with other varieties or crops (Duchêne, 2016; Duchêne *et al.*, 2014).

Although grapevines have several survival strategies (*e.g.*, deep root systems or efficient stomatal control), viticulture is strongly dependent on climate (Fraga *et al.*, 2012). With more extreme events being expected in Europe (Beniston *et al.*, 2007; Hov *et al.*, 2013; IPCC, 2012; IPCC, 2018), additional methods will be required in order to adapt to and mitigate climate change (Soja *et al.*, 2011; van Leeuwen *et al.*, 2019a; van Leeuwen *et al.*, 2019b). Adaptation to higher temperatures include changing plant materials and modifying viticultural techniques. van Leeuwen *et al.* (2019a) have outlined the best available practices to make vineyards more resilient to drought, including planting drought resistant plant material (rootstocks), modifying the training system, or selecting soils with greater water-holding capacity.

CONCLUSIONS

The main purpose of the study was to capture the coincidences of extreme temperature and phenological events of grape varieties in Leytron, Switzerland. The comparison of various methods showed that the methodology of Siegmund *et al.* (2016) seems to be the most appropriate for studying extreme coincidences. The results showed that there were much more such events between 2003 and 2017 than in earlier years (1978–2018). Some phenophases (bud burst and flowering) are less robust in response to extreme temperature, but only significance results were obtained between bud development and inflorescence merge and ripening of berries. While we found differences, we did not find any statistically significant evidence of some grape varieties being more robust or sensitive to temperature extremes than other varieties. However, it might be possible to obtain statistically significant results when comparing grapevine varieties using the proposed methodology on larger data sets from other regions. The observed patterns in our study could provide new insights for winemakers to help make decisions about vineyard management in the face of climate change. However, in order to generalise the statements and findings, this research and methodology would need to be applied to other datasets from different grape varieties in other regions.

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