Strong volcanic-induced climatic shocks on historical Moselle wine production

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Abstract. In central and southern Europe, grapevine is a climate-sensitive agricultural product of large economic importance, both in historical times and today. We systematically investigated the climatic impact, focusing on volcanic-forced abrupt cooling, on two long annual records of wine production quantity (spanning 1444–1786) from the Moselle Valley in present-day Luxembourg, close to the northern limit of viticulture in Europe. We present a consistent picture of the impact of volcanic eruptions on wine production through climate. To this end, we applied superposed epoch analysis – an appropriate method for detecting episodic signals in non-stationary time-series – in combination with a bootstrap procedure to estimate the statistical significance. We also assessed the long-term relationship between different annual and seasonal climate parameters and wine production in the Moselle Valley. Robust and highly significant wine production declines occurred in the years immediately following major volcanic events. Warmer, and to a lesser extent drier, climate condition had a moderately strong, but persistent, positive effect on wine production. We also find a volcanic cooling signature in spring and summer in temperature reconstructions. However, the detected volcanic signature in the Moselle Valley wine production is considerably stronger than the one found for Central Europe in tree-ring data and is instead more akin to the strong volcanic signature present in Fennoscandian tree-ring series. On the basis of our findings, we encourage further compilation, publication, and analyses of additional wine production series containing unique biological and climatic information.

1 Introduction

The climatic response to volcanic forcing during the past few millennia has been studied intensively from local to global scales typically using tree-ring data from strongly temperature-limited growth environments. Impacts on agricultural productivity, including on viticulture, in less extreme climatic settings remains far less well understood. The study of long time-series of agricultural productivity, like grapevine harvest quantities, offers insights into the effects of such abrupt cooling on biological records with properties possibly differing from those of tree-ring series. This, in turn, may shed new light on still unresolved

questions about the effects volcanic-induced cooling have on tree growth in addition to gaining a better understanding of the role of major volcanic events for past agriculture.

Grapevine (henceforth 'vine') is a highly climate-sensitive crop whose phenology is comparatively well understood (Jones et al., 2005; Bock et al., 2013; Droulia and Charalampopoulos, 2022). An increasingly warmer climate, with longer growing

25 seasons, benefits viticulture (vine growing) near its latitudinal and altitudinal limits (Malheiro et al., 2010; Guiot et al., 2023), whereas climatic warming at the same time can have adverse effects on viticulture in regions with a hot and dry Mediterranean climate (Cook and Wolkovich, 2016; Venios et al., 2020). Grapes were the most important cash crop, of an economic importance only second to grain, in much of Europe during the medieval and early modern periods, and vine is and was more climate-sensitive than grain (Pfister and Wanner, 2021). In Central Europe, the quantity of the grape harvest was positively

30 correlated to June–July temperature, the quality to July–September (and especially August) temperature, and the harvest dates to April–July/August temperature (Pfister, 1981; Pfister et al., 2023). Viticulture in Central Europe is, and was, especially sensitive to the effect of spring frost (Meier et al., 2018). The strong cooling during the climax of the Little Ice Age *c.* 1570–1710 (Wanner et al., 2022) made viticulture non-viable in parts of Central Europe – with considerable economic and social consequences (Landsteiner, 1999).

35 Large, but more short-lived, reductions in vine harvests – and thus wine production declines – could be triggered by sharp volcanic-induced cooling. Major volcanic eruptions have a significant impact on climate (Robock, 2000; Oppenheimer, 2011) through a negative radiative forcing related to an increased atmospheric loading of aerosols and dust, and can induce significant global to hemispheric scale cooling for one to several years (Stoffel et al., 2015; Sigl et al., 2015; Burke et al., 2023). The climate effect of an eruption does not only depend on its magnitude, but also on factors such as the geographical position of

40 the volcano and the season of the eruption (Guillet et al., 2017). Quantitative estimates of volcanic-induced cooling during pre-industrial times have mostly been derived from large-scale temperature reconstructions based on tree-ring data (Schneider et al., 2015; Stoffel et al., 2015; Wilson et al., 2016; Anchukaitis et al., 2017; Büntgen et al., 2021). In altitudinal and latitudinal tree-line ecotones, tree growth is particularly sensitive to summer temperature (Körner, 2021) and short-term climatic perturbations are archived in anomalies of annual ring width or wood density (Esper et al., 2016; Hartl-Meier et al., 2017). The precise annual

45 dating of tree-ring chronologies allows for a clear attribution of temperature deviations to volcanic eruptions (Anchukaitis et al., 2012; D'Arrigo et al., 2013; Esper et al., 2013a; Schneider et al., 2017).

The adverse impacts on agricultural productivity and, hence, on human society of volcanic-induced cooling in pre-industrial times have been well-documented in recent scholarship (D'Arrigo et al., 2020; Guillet et al., 2020; Huhtamaa et al., 2022; Stoffel et al., 2022; White et al., 2022; Martin et al., 2023). This is, in particular, the case at the northern edge of grain

50 agriculture in Europe (Ljungqvist et al., 2021, 2024). The effects of volcanic-induced cooling on viticulture in pre-industrial Europe remains less well understood. However, it has been demonstrated that larger, especially tropical, volcanic eruptions resulted in significantly later grape harvest dates for one to two years after the volcanic event (Meier et al., 2007; Guillet et al., 2017; Pfister and Wanner, 2021).

Numerous records, not least from France and Switzerland, exist of grape harvest dates (Yiou et al., 2012). They have been

55 proven to be strongly related to spring and summer temperatures, and have been utilised in numerous documentary-based

temperature reconstructions (e.g., Chuine et al., 2004; Kiss et al., 2011; Možný et al., 2016; Labbé et al., 2019), and also drought reconstructions (Brázdil et al., 2016), despite possible biases in the long-term trends (Garcia de Cortazar-Atauri et al., 2010; Garnier et al., 2011). Grape harvest dates have been proven to be particularly skilful in capturing extreme years (Maurer et al., 2011) such as those frequently following volcanic forcing events (Sigl et al., 2015). Likewise, a number of long wine

60 price series exists from different portions of Europe (Allen and Unger, 2019), but the possible climate signal embedded in the wine price series remains relatively unexplored. In contrast to grape harvest dates and wine price series, long and continuous series of wine production (or grapevine harvest quantity or quality) are rare for medieval and early modern Europe (see, though, the recently published ones by Pfister et al., 2023). However, two long annual wine production quantity records, covering 1444– 1786 with gaps, were already published by Yante (1985). They derive from Grevenmacher and Remich in the Moselle Valley,

65 in present-day Luxembourg, close to the latitudinal limit of European viticulture (Fig. 1a–b).

In this article we systematically investigate the impact from climate, with particular focus on the influence from volcanic forcing, on the two above-mentioned long wine production quantity series. We will first assess the effects of volcanic forced cooling on wine production using superposed epoch analysis (SEA) appropriate for studying episodic events in non-stationary time-series. Then, we will evaluate the effects of volcanic forcing on Moselle Valley pre-industrial climate and explore whether

70 the wine production series contribute information useful for understanding volcanic-induced cooling in the region between the Alps and Scandinavia in comparison to temperature-sensitive tree-ring data. Finally, we will investigate both the short- and long-term relationship between different annual and seasonal climate parameters and wine production quantities in order to understand and constrain the effects of climate on wine production variability. Through utilising bootstrap and phase-scrambling- based techniques to estimate significance, we intend to pay particular attention to issues related to statistical significance.

75 ## 2   Materials and methods

In this section we start with describing the wine production data (Section 2.1), followed by the volcanic forcing dataset (Section 2.2), and then the (palaeo)climate series (Section 2.3). All the datasets are summarised in Table 2. We end the section with describing the various statistical methods applied (Section 2.4).

2.1   The Moselle Valley wine production series

80 The two annual wine production quantity series from Grevenmacher and Remich in the Moselle Valley (49.5°N, 6.35°E) of present-day Luxembourg are based on official records of a tax of one-ninth levied on the wine production. They cover the 1444– 1786 period, though with a gap between 1684–1741 (except for the years 1698–1701) in connection with the French occupation of Luxembourg (Yante, 1985). While the tax was originally levied, when introduced in the 13th and 14th centuries, on every ninth basket of grapevines harvested, it soon instead become levied on every ninth barrel of wine produced. However, the

85 number of barrels of wine produced closely followed the number of baskets of grapevines harvest. Thus, the number of barrels of wine produced mimics the quantity of the vine harvest. It is uncertain to what extent changes over time in tax exemptions affected the wine quantity at inter-annual and longer time-scales. Furthermore, the tax appears in fact to, at times, have been
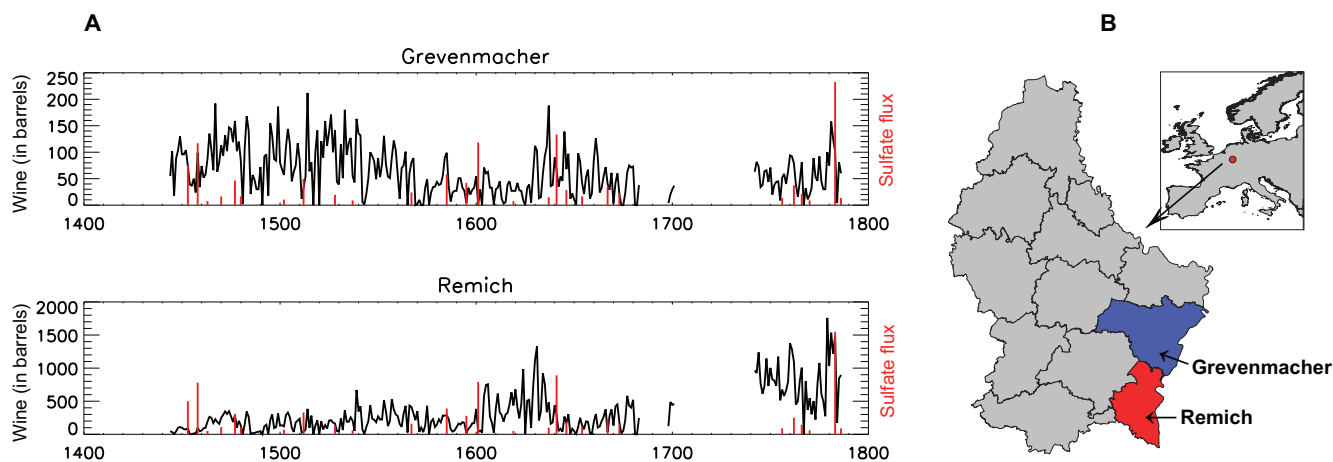
Figure 1. A Annual wine quantities in barrels for each series (*in black*) and volcanic forcing years (*in red*). **B** Location of the two sites with wine data from 1444–1786 (with gaps) in the Moselle Valley of Luxembourg.

both higher and lower than one-ninth of the wine production. The degree of fraud and resistance to taxation might also have varied over time (see also Pfister, 1984). Sufficient to say is that the long-term trend in the Grevenmacher and Remich series are

90 not reliable. The source-critical problems associated with tithe records to estimate actual agricultural productivity variations have been extensively treated in the agrarian history literature (e.g., Kain, 1979; Le Roy Ladurie and Goy, 1982; Leijonhufvud, 2001; Skoglund, 2023). Grevenmacher shows a long-term rather stable, or slightly decreasing, production trend, whereas Remich shows a long-term production increase (Fig. 1a). Nevertheless, the correlation coefficients between the Grevenmacher and Remich series for linearly detrended and 11-year high-pass filtered data, respectively, are $r = 0.55$ and $r = 0.62$. Both

95 correlations are significant at a $p = 0.01$ level (two-tailed test).

Modern observations show that temperature is the single most important climatic factor for viticulture in the Moselle region (Urhausen et al., 2011). The soil in Grevenmacher is limestone and in Remich is alluvial. Grain is the main crop but terraces of vines are widespread too (Yante, 1985). The annual mean temperature during the twentieth century was around 10°C with around 650 mm annual precipitation and slightly over 1400 hours of sunshine. Years with less than 500 mm pre-

100 cipitation tend to produce the best wine. Spring frost is a known problem for viticulture in the region (Meier et al., 2018). The Moselle Valley was during the early modern period a rather marginal viticulture area (about 90% of the wine was white) with often relatively low wine quality, with the wine of Remich considered superior to that of Grevenmacher. Consequently, the vine was grown to much larger extent in Remich than in Grevenmacher (Yante, 1985)).

2.2 Volcanic forcing data

105 We employ the volcanic stratospheric sulfur injection data from Toohey and Sigl (2017), an updated version of Sigl et al. (2015), that is utilised for the recommended forcing in state-of-the-art PMIP4 'past1000' climate model simulations (Jungclaus et al., 2017). This dataset provides forcing year, not eruption year (which is sometimes unknown), and depending on the seasonality

Table 1. Year and flux (in kg/km^2) of the volcanic forcing events 1444–1786 based on Toohey and Sigl (2017). We include the volcanic events occurring 1684–1741 when we have a gap in the wine production series because the events are used for the SEA analysis based on climate extremes.

Year	NH flux [kg/km^2]	Year	NH flux [kg/km^2]
1453	24.80	1646	12.70
1458	35.30	1654	6.20
1463	3.20	1667	18.30
1470	7.30	1673	5.90
1477	27.00	1693	6.96
1480	8.70	1695	24.72
1502	5.30	1707	5.71
1510	12.10	1720	3.77
1528	5.70	1721	4.28
1537	4.50	1729	25.37
1554	5.20	1739	18.09
1567	13.20	1755	6.20
1585	23.30	1762	9.30
1595	11.80	1766	13.20
1600	38.10	1770	3.70
1637	6.80	1783	109.50
1640	41.10	1786	4.40

of the eruption the peak forcing year can be the same year as eruption year or the following year. Toohey and Sigl (2017) used composite ice-core data from Greenland and Antarctica, separately, to generate a robust list of dates of volcanic eruptions. We

110   only use the dates for forcing events with aerosol loading in the Northern Hemisphere (NH) (flux is provided as the deposited sulfate found in the ice cores given in kg/km^2). We restrict our list to those eruptions since it is likely that even strong Southern Hemisphere extra-tropical eruptions do not contribute much to an aerosol loading in the NH.

For use in the superposed epoch analysis we identify key years with NH volcanic forcing of various strengths. In the Toohey and Sigl (2017) NH flux series, for the period we use in the analysis, there are 34 eruptions listed with strengths above 0 (the

115   smallest eruption in the series is near 3.2 kg/km^2); there are 28 eruptions stronger than 5; 16 stronger than 10; 11 stronger than 15, and 9 stronger than 20 kg/km^2. In our analyses we use all the eruptions as recent results suggest that weak eruptions can have significant climate effects (Chim et al., 2023). However, we also test the effects of only using eruptions larger than the thresholds mentioned above. The eruption years included are listed in Table 1.

2.3 Climate data

120 Instrumental climate data have only a short period of overlap with the Grevenmacher and Remich wine production series. The closest instrumental temperature station to Luxembourg in the homogenised European Climate Assessment (ECA) temperature dataset (Squintu et al., 2019) is the monthly-averaged data for De Bilt in The Netherlands (van Engelen and Geurts, 1985) at a distance of about 300 km. Data from De Bilt overlaps with the wine production series from 1742 to 1786, covering only a period of 45 years.

125 We therefore employ reconstructed series of temperature and precipitation, as summarised in Table 2. We use seasonally resolved gridded reconstructed temperature data from Luterbacher et al. (2004) and Xoplaki et al. (2005) (henceforth only cited as Luterbacher et al. (2004)) and seasonally resolved gridded reconstructed precipitation from Pauling et al. (2006) back to 1500 (Table 2). Both the Luterbacher et al. (2004) and Pauling et al. (2006) reconstructions include instrumental data during the 18th century. Data are extracted from the local grid-cell(s) covering Luxembourg. In addition, we use the seasonal

130 resolved reconstructed temperature data from Dobrovolný et al. (2010), which is available as a Central European average for the same period. For the full period since 1444 we use the June–August temperature reconstruction by Luterbacher et al. (2016), as updated by Ljungqvist et al. (2019), based mainly on tree-ring data but also containing the documentary-based June–August season data from above-mentioned Dobrovolný et al. (2010) reconstruction. Furthermore, we employ for the full period the solely tree-ring-based NTREND gridded field reconstruction (Anchukaitis et al., 2017) of May–August temperature. For

135 comparisons against volcanic-induced cooling in the Alpine region, we use the June–September temperature reconstruction from the Lötschental, Switzerland, which is derived from a strong temperature signal in maximum latewood density tree-ring series (Büntgen et al., 2006). June–August soil moisture (drought) conditions for the entire period are obtained from the tree-ring width based gridded Old World Drought Atlas (Cook et al., 2015) providing self-calibrated Palmer Drought Severity Index (scPDSI) values (van der Schrier et al., 2011).

2.4 Statistical methods

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The episodic nature of the volcanic eruptions is an advantage when analysing their effects on variables with unknown, or even dubious, low-frequency variations and trends, such as wine production quantities. We simply compare the size of the considered time-series (wine production or climate conditions) in the years immediately following the eruptions with the average size in the years before (usually five years). Using superposed epoch analysis (SEA; Chree, 1913, 1914; Rao et al., 2019), we calculate

145 the average of this difference across K eruptions, that are covered by the considered time-series – so the number of eruptions might vary slightly for different time-series – and stronger than the chosen threshold. We standardised the time-series to zero mean and unit variance before conducting the SEA. The significance is estimated by a bootstrap procedure, assuming only that the eruptions are independent. If we have K eruptions we pick K random years in the whole period under consideration and calculate the superposed epochs from these years. We do this 3000 times to get a distribution of the SEA under the null-

150 hypothesis that volcanic eruptions have no impact on the considered time-series (e.g., wine production). Comparing the original SEA with this distribution, we can calculate the p-value as the probability of having a lower SEA than the observed. We report

Table 2. Wine production data, (palaeo)climate and volcanic forcing data series used in this study with information of parameters, period covered, grid-cell (centre coordinates), season, data type, AR1, and data source.

Data-sets	Period	Grid-cell	Season	Data type(s)	AR1	Source/reference
Wine production data						
Grevenmacher	1444–1786	49.5°N, 6.35°E	Annual	Documentary	0.41	Yante (1985)
Remich	1444–1786	49.5°N, 6.35°E	Annual	Documentary	0.62	Yante (1985)
Temperature data						
Moselle temperature	1500–	49.5°N, 6.5°E	Seasonal	Multi-proxy/instr.	0.04[a]	Luterbacher et al. (2004); Xoplaki et al. (2005)
Central Europe	1500–	Not gridded	Seasonal	Documentary	0.06[a]	Dobrovolný et al. (2010)
EuroMed2k (updated)[b]	Full	47.5°N, 7.5°E	Jun–Aug	Tree-ring/doc.	0.67	Ljungqvist et al. (2019)
NTREND	Full	47.5°N, 7.5°E	May–Aug	Tree-ring	0.45	Anchukaitis et al. (2017)
Lötschental, Switzerland	Full	46.42°N, 7.83°E	Jun–Sept	Tree-ring	0.55	Büntgen et al. (2006)
Hydroclimate data						
Moselle precipitation	1500–	49.5°N, 6.5°E	Seasonal	Multi-proxy/instr.	0.07[a]	Pauling et al. (2006)
scPDSI	Full	49.5°N, 6.5°E	JJA	Tree-ring	0.39	Cook et al. (2015)
Volcanic forcing data						
NH flux	Full	Not gridded	Annual	Ice-core	—	Toohey and Sigl (2017)

[a] Mean AR1 of the four different seasonal windows (December–February, March–May, June–August, and September–November).

[b] Updated by Ljungqvist et al. (2019) from the first EuroMed2k reconstruction version published by Luterbacher et al. (2016).

significance in the SEA at both the $p = 0.05$ and $p = 0.01$ significance levels. Furthermore, our results are robust to changes in the details of the analysis such as in the length of the epochs or whether the average is calculated over the whole epoch and not just the half preceding the eruptions. The SEA results are based on time-series standardised to unit variance over the whole period. However, similar results are obtained when the standardization is performed individually over running-windows (corresponding to variance equalisation).

To further investigate the relationship between climate and wine production quantities we calculated the Pearson correlation coefficient (r) between the wine production series and the various (palaeo)climate reconstructions. The significance of correlations were calculated using $p = 0.05$ with a phase-scrambling test which is more conservative than the common Student's t-test (for details, see Ljungqvist et al., 2022, 2023). To emphasise inter-annual variability, we employed 11-year high-pass filtering of the data. For studying low-frequency variability we employed an 11-year low-pass filter. Inter-annual fluctuations, as well as inter-annual noise, is suppressed using data filtered in this way. While we have used a simple 11-year smoothing filter, based on subtraction from the time-series a smoothed version, other more complicated filters (e.g., Gaussian filters) provided almost identical results. During an exploratory data analysis phase, we also compared the use of the parametric Pearson correlation coefficient with the non-parametric Kendall's and Spearman correlation coefficients, finding that they resulted in similar correlation patterns.
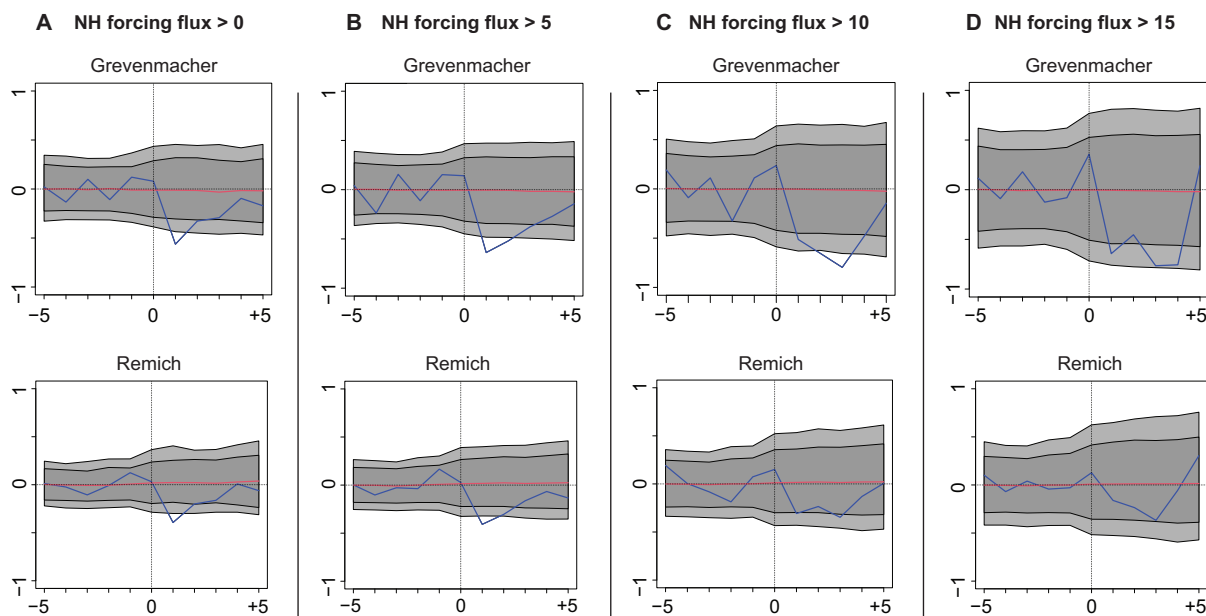
Figure 2. Superposed epoch analysis (SEA) of volcanic forcing, after NH forcing flux size, on standardised wine production quantity for Grevenmacher, Remich. The grey bands indicate $p = 0.05$ and $p = 0.01$ significance levels, calculated by a bootstrap method (generated random dates).

3 Results

In this section we study the influence of volcanic eruptions on wine production (subsection 3.1), the influence of volcanic eruptions on climate (subsection 3.2), and the influence of climate extremes on wine production (subsection 3.3). We will mainly
170 focus on the episodic connection using SEA analysis, while we will additionally use correlation analysis in subsection 3.3. Together, this will provide evidence for a volcanic and climatic influence on the wine production quantity, mainly through spring and summer temperatures.

3.1 Effects of volcanic forcing on Moselle Valley wine production

A main focus of this study is the effects of volcanic-forced abrupt cooling on the Moselle Valley wine production. Super-
175 posed epoch analysis (SEA) reveals a strong decrease in wine production the year following volcanic forcing events for both Grevenmacher and Remich. The SEA signal itself is shown in Fig. 2 with the blue curves, while the dark and light shaded bands indicate the $p = 0.01$ and $p = 0.05$ significance levels, respectively. This volcanic-related production decrease pattern is similar regardless of whether all volcanic events are included or only those exceeding certain thresholds for NH forcing flux (as demonstrated in the different panels in Fig. 2).

180   In general, we find a strong, significant, and consistent decrease in wine production in the years following volcanic forcing events for both the Grevenmacher and Remich series. For all thresholds the signal (blue curve in Fig. 2) is about half a standard deviation and the p-value is below 0.05 and often below 0.01 (shaded regions in Fig. 2). Slightly smaller signals are found for Remich compared to Grevenmacher. Including all eruptions, we find the largest signal in the first year after the eruptions. The (taxed) wine production was even zero, or close to it, in the first year following certain major volcanic events: 1481, 1601,

185   1674, 1767, and 1784. However, when increasing the threshold and only including stronger (and fewer) eruptions we see a tendency for the strongest wine production decrease to be delayed. For the largest eruptions the strongest signals appear 3–4 years after the eruptions.

The bands indicating the significance levels expand with increasing threshold due to the fewer eruptions included (Fig. 2). When only including larger volcanic events, exceeding an estimated NH forcing flux of >10, a wine production decrease that

190   is significant at the $p = 0.01$ level is only found the third year after the volcanic event – and only for Grevenmacher. Weaker, less significant, decreases are also detected the first and second years after the volcanic event, with the Remich series showing a broad decrease for years 1–3 after such strong eruptions.

3.2   Effects of volcanic forcing on Moselle Valley pre-industrial climate

We have performed SEA from volcanic forcing events on temperature and precipitation series (local grid-cells when applicable)

195   from the Moselle Valley (see Table 2). Figure 3 summarises the strengths of the connection by reporting the smallest p-values (two-tailed test) taken over years 0–5, i.e., from the year of the eruptions and the following 5 years. These p-values basically reflect the strength of the SEA signals.

We find that significant connections for the temperature series mainly in spring and summer. For example, p-values below 0.02 are found for the temperature series by Dobrovolný et al. (2010) and Luterbacher et al. (2004) only for the March–May

200   and June–August seasons. For temperature in spring and summer the lowest p-values are found for lag 0 or 1 year (not shown). The significant signals in the temperature series all correspond to coolings. Similar results are obtained using only eruptions larger than 5 kg/km^2, while the situation for higher thresholds (and correspondingly fewer eruptions) is more muddled. For precipitation, significant signals corresponding to wetter conditions are found in annual and September–November reconstructions.

205   We emphasise the weak and insignificant volcanic signatures in the tree-ring based temperature reconstructions (EuroMed2k, NTREND, and Lötschental) for the Central Europe region. This less distinct volcanic signature stands in sharp contrast to the strong and clear wine production quantity reduction after volcanic forcing events, that reaches significance well below the $p = 0.01$ level for several years even when including minor forcing events (Fig. 2).

3.3   Effects of climate on Moselle Valley wine production

210   We have identified the 20 most extreme years (for each of the four seasons) for a selection of the climate series in Table 2. Thus, for temperature series we find the 20 most warm and cold years and for precipitation the 20 most wet and dry years. These extremes are identified from the raw series without detrending. We then conducted SEA to identify the responses in the
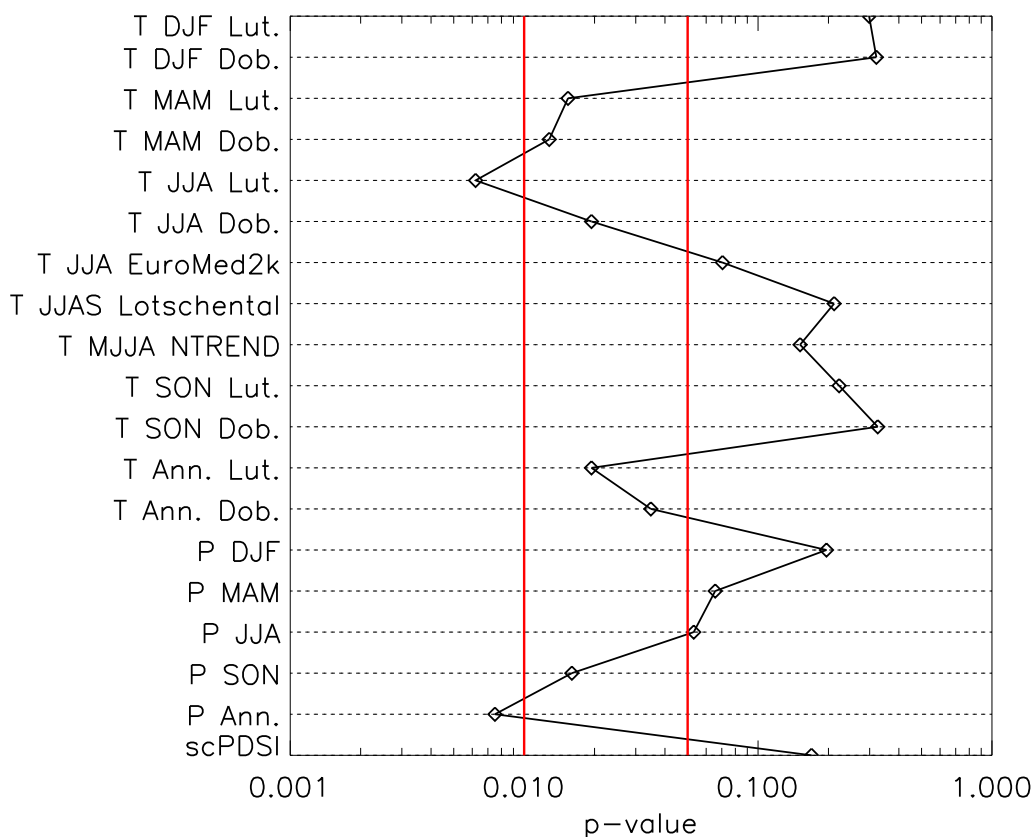
Figure 3. For each climate series in Table 2, a SEA based on the years of the volcanic forcing event has been performed. The lowest *p*-value (two-tailed test) in the year of the volcanic forcing event and the following 5 years are shown. Volcanic forcing events of all strengths are included. The x-axis is logarithmic, and *p*-values of 0.01 and 0.05 are shown with the red vertical lines. The significant signals in the temperature/precipitation series all correspond to colder/wetter conditions.

two wine production series to these four kinds of extremes for each season. The results are shown in Table 3 which reports the *p*-values and the signs of the significant responses.

215   We find that the spring (MAM) stands out from the other seasons with significant responses for all four kinds of extremes. We also note that consistent directions of the responses are found; increasing wine production for warm/dry conditions and decreasing production for cold/wet conditions. The climate series from Luterbacher et al. (2004) and Pauling et al. (2006) show consistent results. Furthermore, we find almost identical results for the Remich and for Grevenmacher wine series. For the other seasons, fewer significant and less consistent responses are found, indicating that the significance in these seasons 220 might partly be due to chance.

Table 3. The p-values for the SEA performed using as key years the 20 warmest/coldest/wettest/driest years, respectively, in the seasonal series of the Luterbacher et al. (2004) temperature reconstruction and the Pauling et al. (2006) precipitation reconstruction on the Remich and Grevenmacher wine production series. The p-values (two-tailed test) were calculated using repeated scrambling of years, see text for details, and p-values below 0.05 are typeset in bold. The lowest p-value (two-tailed test) in the year of the eruptions and the following 5 years are shown in the table. (+) and (–) designate the direction of the effect on the wine series, where the strongest excursion on the SEA curve inside the 0 to +5 years is used (which is often year 0 or +1).

Type	Climate series	Season	Wine series	p-value
Warmest	Luterbacher et al. (2004) temp.	DJF	Remich	0.079
Coldest	Luterbacher et al. (2004) temp.	DJF	Remich	**0.031 (–)**
Wettest	Pauling et al. (2006) precip.	DJF	Remich	**0.042 (–)**
Driest	Pauling et al. (2006) precip.	DJF	Remich	**0.012 (–)**
Warmest	Luterbacher et al. (2004) temp.	DJF	Grevenmacher	0.483
Coldest	Luterbacher et al. (2004) temp.	DJF	Grevenmacher	0.054
Wettest	Pauling et al. (2006) precip.	DJF	Grevenmacher	**0.007 (–)**
Driest	Pauling et al. (2006) precip.	DJF	Grevenmacher	0.164
Warmest	Luterbacher et al. (2004) temp.	MAM	Remich	**0.005 (+)**
Coldest	Luterbacher et al. (2004) temp.	MAM	Remich	**0.008 (–)**
Wettest	Pauling et al. (2006) precip.	MAM	Remich	**0.019 (–)**
Driest	Pauling et al. (2006) precip.	MAM	Remich	**0.010 (+)**
Warmest	Luterbacher et al. (2004) temp.	MAM	Grevenmacher	**0.003 (+)**
Coldest	Luterbacher et al. (2004) temp.	MAM	Grevenmacher	**0.022 (–)**
Wettest	Pauling et al. (2006) precip.	MAM	Grevenmacher	**0.002 (–)**
Driest	Pauling et al. (2006) precip.	MAM	Grevenmacher	**0.006 (+)**
Warmest	Luterbacher et al. (2004) temp.	JJA	Remich	0.079
Coldest	Luterbacher et al. (2004) temp.	JJA	Remich	**0.016 (–)**
Wettest	Pauling et al. (2006) precip.	JJA	Remich	0.323
Driest	Pauling et al. (2006) precip.	JJA	Remich	**0.006 (+)**
Warmest	Luterbacher et al. (2004) temp.	JJA	Grevenmacher	0.083
Coldest	Luterbacher et al. (2004) temp.	JJA	Grevenmacher	**0.035 (–)**
Wettest	Pauling et al. (2006) precip.	JJA	Grevenmacher	0.090
Driest	Pauling et al. (2006) precip.	JJA	Grevenmacher	0.129
Warmest	Luterbacher et al. (2004) temp.	SON	Remich	**0.020 (+)**
Coldest	Luterbacher et al. (2004) temp.	SON	Remich	0.058
Wettest	Pauling et al. (2006) precip.	SON	Remich	0.051
Driest	Pauling et al. (2006) precip.	SON	Remich	**0.049 (–)**
Warmest	Luterbacher et al. (2004) temp.	SON	Grevenmacher	**0.447 (+)**
Coldest	Luterbacher et al. (2004) temp.	SON	Grevenmacher	0.181
Wettest	Pauling et al. (2006) precip.	SON	Grevenmacher	0.131
Driest	Pauling et al. (2006) precip.	SON	Grevenmacher	0.060
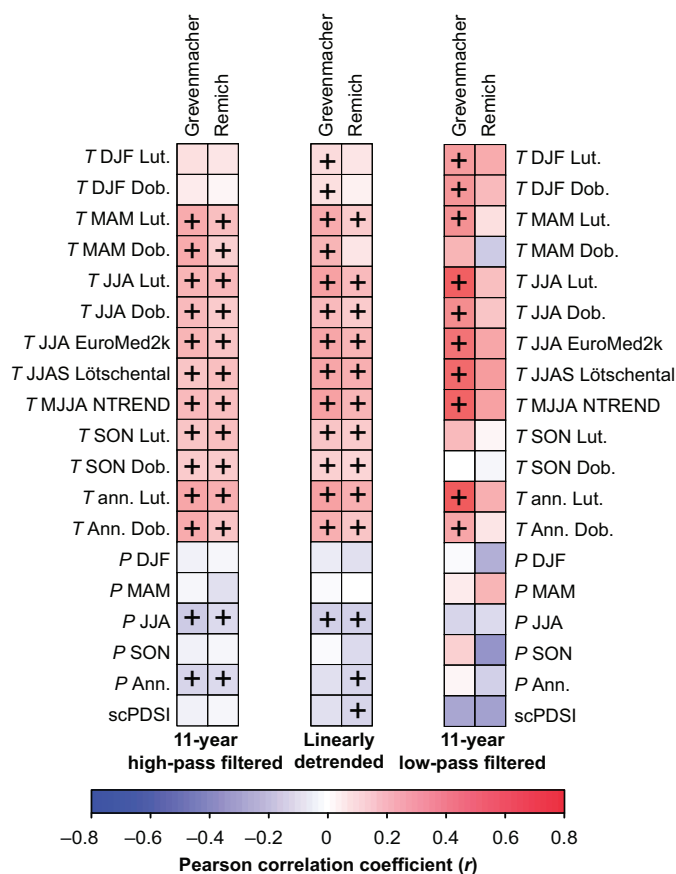
Figure 4. Correlation matrix between the (palaeo)climate series listed in Table 2 and wine production quantity data from Grevenmacher and Remich for 11-year high-pass filtered data, linearly detrended data, and 11-year low-pass filtered data (after linearly detrending). Correlations significant at $p = 0.05$ with the phase-scrambling test are marked with a plus sign (+).

Through correlation analyses we explored the long-term relationships between wine production and seasonal and annual temperature, precipitation and soil moisture. We started the analyses with De Bilt instrumental series. The correlation between the De Bilt instrumental series and the Grevenmacher series, over their 45-year period of overlap 1742–1786, is $r = 0.46$ using 11-year high-pass filtered data for JJA temperature for both. For Remich the result is $r = 0.29$ (just below significance).

225 Furthermore, annual mean temperature for De Bilt shows significant positive correlations with Grevenmacher and Remich of $r = 0.46$ and $r = 0.42$, respectively, using 11-year high-pass filtered data. No other seasons, neither for linearly detrended data nor high-pass filtered data, reveal any significant correlation between wine production and the De Bilt instrumental temperature series.

Using reconstructed temperature data covering the entire, or the majority, of the length of the Grevenmacher and Remich

230 wine production series shows similar, but more significant, correlation patterns as found using the short De Bilt instrumental series. Mostly significant correlations are found between temperature and wine production quantities between both 11-year

high-pass filtered and linearly detrended data (Fig. 4). These correlations are, in general, slightly stronger for Grevenmacher than for Remich. The most significant association is the positive relationship between spring, summer and autumn temperature, as well as for the annual mean, and wine production (i.e., warm = high wine production and *vice versa*). Correlations are

235   weak for winter temperatures being entirely outside the growing season (Fig. 4). Significant positive correlations are also found between (palaeo)climate series and the Grevenmacher series using 11-year low-pass filtered data. While some of the correlations are slightly stronger than those for high-pass filtered or linearly detrended data, the fewer degrees of freedom render a lower number of them significant. Notably, for Remich not a single correlation using 11-year low-pass filtered data is significant, although most of the correlations are positive and of comparable strength as those for high-pass filtered and linearly

240   detrended data.

     Negative relationships, in general less significant than those with temperature, are found in the hydroclimate between precipitation and soil moisture and wine production (i.e., wetter = lower wine production and *vice versa*) for both 11-year high-pass filtered data and linearly detrended data. Significant relationships with hydroclimate are mostly restricted to the summer season and to the annual mean. We note that while the correlation-based results provide the strongest signal for summer, the SEA-

245   based results using extreme years instead show the strongest signal in spring. Nevertheless, both analyses reinforce the finding that warm and dry years and growing seasons benefited the wine production, while cold and wet years had an adverse effect. For hydroclimate, no significant correlations are found with either the Grevenmacher or Remich series using 11-year low-pass filtered (palaeo)data.

4   Discussion

250   ### 4.1   The climate signal embedded in the wine production quantities

We have found a highly significant climatic and volcanic signature in the Moselle Valley wine production data. These signals remain persistent, from late medieval times until the end of the early modern period, despite uncertainties to what extent the 'ninth' tax records reflect the actual wine production quantities in tandem with a relatively high noise level in the employed (palaeo)climate series. The stronger temperature response in Grevenmacher (Fig. 4), compared to Remich, is consistent with a

255   stronger volcanic response there (Fig. 2). It is difficult to assess to what extent the decrease in wine production during the 1570s was related to war and the simultaneously occurring climatic cooling. However, climate certainly played a part and this was also a period of widespread grain harvest failures, high livestock mortality, extreme food prices, and widespread famine (White et al., 2018; Pfister and Wanner, 2021; Ljungqvist et al., 2024). Despite the strong detected climate signal in wine production quantities, showing that cold and wet climate conditions was an important constraint for wine production not only during

260   extreme periods, it is important to notice that the different long-term trends in the two wine production records show that human agency to a large extent could overcome climatic constraints. The main way to do this was to increase the acreage of vine grown and to select favourable micro-site locations for vineyards.

     The reduced wine production quantities for up to several years following larger volcanic forcing events can, in part, be attributed to the fact that that strong eruptions cause aerosols to linger for a longer period in the atmosphere, and induces

265 feedback mechanisms in the climate system that prolongs cooling (Toohey et al., 2016). In part it can also be attributed to a
biological memory effect, and cold and frost damage, of the vine stocks during years with very poor growth conditions (Pfister
and Wanner, 2021). Biological memory effects are very well-documented for tree growth (Esper et al., 2015; Hartl-Meier
et al., 2017). Especially, tree-ring width depends to some degree on growth conditions in the previous year and resulting
climate reconstructions often show more auto-correlation than the instrumental target (Ljungqvist et al., 2020). As expected,

270 auto-correlation values (AR1) reported for the time-series used in this study are higher, if biological archives are involved
compared to documentary-based records (see Table 2). But while a limited immediate response to abrupt volcanic cooling
has been reported for many tree-ring width records (Esper et al., 2015), as opposed to maximum latewood density (MXD)
records (Hartl-Meier et al., 2017), this seems not to be the case for the wine production series. Thus, in this respect wine
production shows a similar behaviour to MXD, potentially indicating that other physiological processes control fruit production

275 than stem increment.

4.2 Further comparison between the volcanic effect on wine production and tree-ring growth

The wine production decline in Grevenmacher and Remich following volcanic forcing events contrasts to the weak volcanic
response for Central Europe in the state-of-the-art gridded NTREND tree-ring-based temperature reconstruction (Anchukaitis
et al., 2017), the mainly tree-ring-based updated EuroMed2k temperature reconstruction (Ljungqvist et al., 2019) as well as

280 the MXD-based Lötschental temperature reconstruction (Büntgen et al., 2006). This reconstruction is primarily composed of
MXD data from tree-rings, a temperature proxy commonly assumed to be little affected by biological memory (Anchukaitis
et al., 2012; Esper et al., 2015). Despite remaining discussions regarding the precise quantification of volcanic signals in MXD-
based reconstructions (Tingley et al., 2014; Edwards et al., 2022), there has been repeated evidence for significant cooling in
MXD-based reconstructions following single events (Guillet et al., 2017; Hartl-Meier et al., 2017) and groups of eruptions at

285 local (Rydval et al., 2017), regional (Esper et al., 2013b) and hemispheric (Wilson et al., 2016; Schneider et al., 2017) scales.

In contrast to a moderate volcanic cooling impact over Central Europe, NTREND and EuroMed2k reveal strong and
widespread cooling in response to tropical eruptions over Scandinavia with a distinct transition between these two regions
over the southern Baltic Sea region at around 55°N. However, NTREND and EuroMed2k contain no tree-ring data in Europe
between 50°N and 60°N making it difficult to pin down the exact location of this transition. The gridded seasonal temperature

290 reconstruction for Europe by Luterbacher et al. (2004), using predominantly documentary data, suggests significant summer
cooling that extends as far south as the northern fringe of the Alpine arc (Fischer et al., 2007), which is better in agreement
with the volcanic impact found here in wine production series from the Moselle Valley. The lack of climate sensitive tree-ring
records from Central Europe (north of the Alpine Arc) is also expressed in reduced values for explained variance at the Moselle
grid-cell compared to the explained variance for, e.g., northern Fennoscandia.

295 Comparison between wine production declines and tree-ring growth declines is complicated by the limited number of major
volcanic forcing events during the comparatively short period covered by the two wine production series. Numerous studies of
temperature-sensitive tree-ring data, from northern Europe and elsewhere, have shown a maximum growth decline (growing
season cooling) during the summer in the year following the volcanic forcing event (Esper et al., 2017). Such a distinct one year

post-eruption cooling is most evident in MXD data, compared to TRW data, owing to the typically stronger correlation with
temperature and the larger biological memory in TRW (Hartl-Meier et al., 2017). Thus, the post-volcanic decrease detected in
this study in wine production quantities is very similar to the post-volcanic growth decline in MXD. Nevertheless, the most
noteworthy feature in the wine production data is the strong and consistent response one year following the volcanic forcing
event even for a low NH flux threshold (> 0 and > 5) that is absent in tree-ring based temperature reconstructions for Central
Europe. At the mid-latitudes, where the wine production data diverges from the tree-ring based temperature reconstructions,
no reconstructions show a significant summer temperature reduction in response to a low NH forcing flux threshold.

We suggest the explanation for the stronger, and more persistent, climate response in the wine production data than in the
tree-ring data is due to physiological differences. In addition to the consistent signal one year following the volcanic forcing
event, there is in the wine production data a 'late response' after big flux events (thresholds >15 and >20). This late signal
is also present in the entirely tree-ring-based NTREND (Anchukaitis et al., 2017) and (weakly) in the Lötschental (Büntgen
et al., 2006) temperature reconstructions (not shown). It is more difficult to come to conclusion about this part of the signal
because there are only few events falling into this category. While it would be interesting to study the climate (and volcanic)
response on tree growth and wine production from the same locations, it would be challenging because temperature-sensitive
and/or precipitation-sensitive tree-ring series rarely are available from vine growing regions with the exception of regions close
to the Alps. Nevertheless, such studies could provide insights into the decorrelation length of climate *versus* differences in the
climate sensitivity of the vine growth and tree-ring growth.

5 Conclusions and outlook

We have systematically investigated the impacts of volcanic forcing events and climate variability on two of the longest wine
production quantity records (spanning 1444–1786 with gaps) in Europe deriving from the Moselle Valley close to the northern
limit of viticulture. We used SEA analysis, which is particularly appropriate for episodic events. The statistical significance
of the SEA was estimated with a bootstrap method. We also assessed the long-term relationship between climate and wine
production using correlation analyses and calculating the significance with a conservative phase-scrambling test.

A strong negative impact of volcanic eruptions on wine production quantity was found in the year, and years, following a
volcanic forcing event (subsection 3.1). This finding is robust under removal of weaker volcanic eruptions. Both SEA based
on climate extremes and correlation analysis (11-year high- and low-pass filtered and linearly detrended) consistently show
that cold and wet conditions are detrimental for wine production (subsection 3.3). Furthermore, following volcanic eruptions
we see anomalously cold and wet conditions in the Moselle Valley region (subsection 3.2) which in the light of these results
from subsection 3.3 indicates negative impacts on the wine production. This is exactly what we find in subsection 3.1. For both
the volcanic impact on climate (subsection 3.2) and the impact of climate extremes on wine production (subsection 3.3), the
largest effect is found in spring and summer. Thus, taken together, these findings present a consistent picture of the effect of
volcanic eruptions on wine production and how it is mediated through climate.

We furthermore note that the detected volcanic signature in the Moselle Valley wine production is distinct and statistically significant (subsection 3.1), while that of tree-ring based temperature reconstructions for Central Europe is neither (subsection 3.2). Based on our findings we conclude that long series of annual wine production quantity contains very valuable biological and climatic information and we, thus, encourage further archival research to compile and publish additional wine
335 production quantity series from across the viticulture regions of Europe.

Code availability. We have used **IDL** and **R** (R Core Team, 2022) version 3.6.3 to program the analysis codes used in this work. In **R** we used the package 'corrplot' (Wei and Simko, 2021) to generate the correlation matrices. Data were read from mixed files using 'base' libraries for text files or 'openxlsx' (Schauberger and Walker, 2021) for Excel spreadsheet files. The superposed epoch analysis was performed with **R** code, available upon reasonable request.

340 *Data availability.* The wine production data can be obtained from Appendix 1 in the article by Yante (1985), pp. 301–307. All used (palaeo)climate data are digitally available from the National Oceanic and NOAA Paleoclimatology/World Data Center for Paleoclimatology:
https://www.ncei.noaa.gov/products/paleoclimatology. The monthly De Bilt temperature series (van Engelen and Geurts, 1985) are available from the KNMI Climate Explorer (Trouet and Van Oldenborgh, 2013):
345 https://climexp.knmi.nl/getindices.cgi?WMO=KNMIData/labrijn&STATION=Tdebilt&TYPE=i

Author contributions. F.C.L. designed the study together with B.C. and P.T. F.C.L., B.C. and P.T performed data analyses, conducted the SEA and the phase-scrambling significance tests. L.S. especially contributed with comparisons between the volcanic signature in wine production data and tree-ring data. All authors interpreted the results and wrote the article together.

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