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Climate change decouples drought from early wine grape harvests in France

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Across the world, wine grape phenology has advanced in recent decades[1–3], in step with climate-change-induced trends in temperature—the main driver of fruit maturation—and drought. Fully understanding how climate change contributes to changes in harvest dates, however, requires analysing wine grape phenology and its relationship to climate over a longer-term context, including data predating anthropogenic interference in the climate system. Here, we investigate the climatic controls of wine grape harvest dates from 1600–2007 in France and Switzerland using historical harvest[4] and climate data[5–7]. Early harvests occur with warmer temperatures (−6 days °C^{-1}) and are delayed by wet conditions (+0.07 days mm^{-1}; +1.68 days PDSI^{-1}) during spring and summer. In recent decades (1981–2007), however, the relationship between harvest timing and drought has broken down. Historically, high summer temperatures in Western Europe, which would hasten fruit maturation, required drought conditions to generate extreme heat. The relationship between drought and temperature in this region, however, has weakened in recent decades and enhanced warming from anthropogenic greenhouse gases can generate the high temperatures needed for early harvests without drought. Our results suggest that climate change has fundamentally altered the climatic drivers of early wine grape harvests in France, with possible ramifications for viticulture management and wine quality.

Wine grapes (*Vitis vinifera* ssp. *vinifera*) are the world's most valuable horticultural crop, and there is increasing evidence that warming trends have advanced wine grape harvest dates in recent decades[1,2,8–12]. Harvest dates are closely connected to the timing of grape maturation, which is highly sensitive to climate during the growing season. Specifically, warmer temperatures accelerate grapevine phenology over the full cycle of development (budburst, flowering, veraison and maturity), whereas increased precipitation tends to delay wine grape phenology[13]. The earliest harvests thus generally occur in years where the growing season experiences warmer temperatures and drought[8].

Along with trends in harvest dates, there have also been apparent shifts in wine ratings[14] and other metrics of wine quality[8,15]. High-quality wines are typically associated with early harvest dates in many of the cooler wine-growing regions, such as France[8,14], and are also favoured by warm summers with above-average early-season rainfall and late season drought. This ensures the vines have sufficient heat and moisture to grow and mature early on, with dry conditions later in the year shifting them away from vegetative growth and towards greater investment in fruit production mid-season[13,16,17]. Overall, both precipitation[18] and temperature[17] contribute to wine quality and the timing of harvest[11,12], although temperature is the most critical factor influencing wine grape phenology[14,19].

These shifting trends in viticulture have led to much recent research to better understand climate controls on wine grape phenology[11,12,20], especially grape harvest dates, and wine quality[14,18,19]. Most research has, however, focused on relatively short, recent timescales (for example, the past 30–40 years[1,10,12]). There has thus been little consideration of the longer-term historical context of recent harvest date trends and possible non-stationarities in the relationship between wine grape phenology and climate. We address these issues by conducting a new analysis using over 400 years (1600–2007) of harvest data from Western Europe[4]. From this database, we construct a multi-site grape harvest date index (hereafter, GHD-Core) by averaging harvest date anomalies from seven regional harvest date time series across France and one site in Switzerland (see Methods for more details). We then analyse the variability and trends in GHD-Core, and compare against instrumental climate data over the twentieth century[21] and proxy-based reconstructions of temperature[5], precipitation[7] and soil moisture[6] (Palmer Drought Severity Index; PDSI) back to 1600. We also test for associated shifts in wine quality for two sites (Bordeaux and Burgundy), using wine quality ratings of vintages over the past 100 years[22].

The GHD-Core series shows pronounced year-to-year variability and a strong trend towards earlier dates in the latter part of the twentieth century (Fig. 1). The latest harvest date anomaly in the record (Fig. 1, left panel) is 1816, the so-called 'Year without a Summer' following the eruption of Mount Tambora in Indonesia[23]. The eruption caused pronounced cooling over continental Europe during the growing season, with harvest dates in GHD-Core delayed over three weeks (+24.8 days). The earliest harvest date anomaly in the record is 2003 (−31.4 days), coinciding with one of the worst summer heat waves in recent history[24]. Mean harvest dates (Supplementary Table 4) were modestly early during the first half of the twentieth century (1901–1950, −5.2 days) and close to the long-term average from 1951–1980 (−1.1 days). In more recent decades (1981–2007), however, average harvest dates were substantially earlier (−10.2 days), exceeding one full standard deviation of harvest date variability calculated for the baseline averaging period (1600–1900, ±7.67 days). This most recent period is significantly earlier than the mean dates from the full previous interval (1600–1980; one-sided Student's t-test, $p \leq 0.0001$). The 1981–2007 period is also earlier than the earliest previous 27-year period (1635–1661, −7.42 days), although results are only marginally significant (one-sided Student's t-test, $p = 0.075$).

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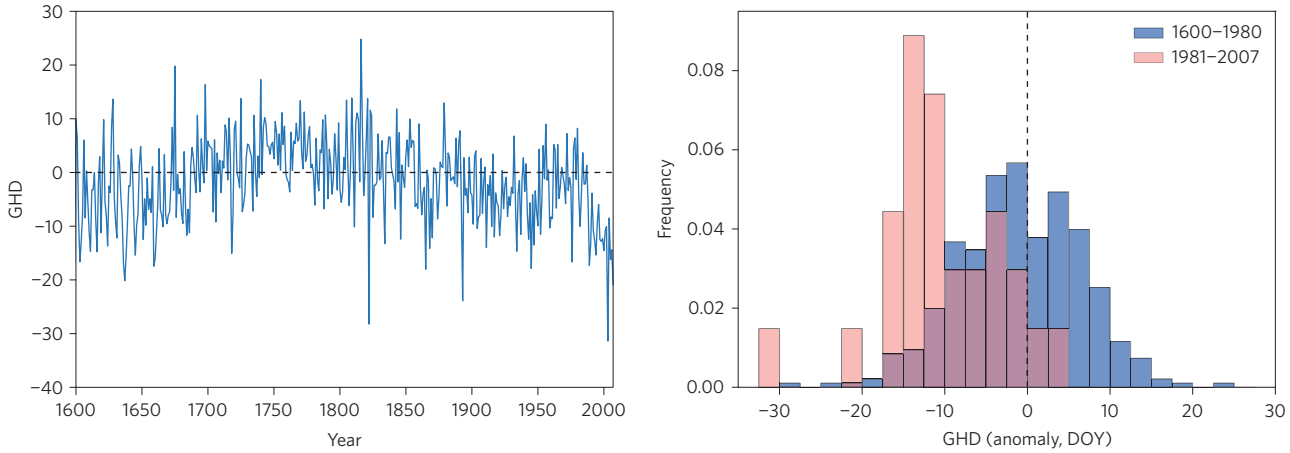

Figure 1 | Grape harvest date anomalies (GHD-Core). Left panel: time series of grape harvest date anomalies, composited from the Alsace, Bordeaux, Burgundy, Champagne 1, Languedoc (Lan), Lower Loire Valley (LLV), Southern Rhone Valley, and Switzerland at Lake Geneva regional harvest date time series in the Daux data set[4]. All anomalies are in units of day of year, calculated relative to the average date from 1600–1900. Right panel: normalized histograms of GHD-Core harvest date anomalies from 1600–1980 (blue) and 1981–2007 (red).

In addition to an overall trend towards earlier harvest dates, there are also substantial changes in the strength of the relationship between climate (temperature, precipitation, PDSI) and GHD-Core (Figs 2 and 3; for individual regional grape harvest date series, see Supplementary Figs 4–11). Most notably, the strength and significance of the moisture relationships (precipitation and PDSI) decline in recent years (Fig. 2, bottom two rows; Fig. 3, centre and right columns), whereas the relationship with temperatures seems relatively stationary (Fig. 2, top row; Fig. 3, left column). For example, GHD-Core correlates negatively (Spearman's rank) with May–June–July (MJJ) temperatures across Western Europe, indicating a strong tendency for earlier harvests during warmer conditions in late spring and early summer. Regional average (dashed box in Fig. 2; 2° W–8° E, 43° N–51° N) MJJ temperatures are the single best predictor of GHD-Core (Fig. 3), explaining 70% of the variance for 1901–1980 and only weakening slightly in the more recent period ($R^2 = 0.64$). Notably, the slope of the regression is similar before and after 1980 (harvest dates advance approximately −6 days per degree of warming), suggesting that the temperature sensitivity of harvest dates has been relatively stationary over time. Correlations between French harvest dates and temperatures in our analysis are similar to previous studies[25]. And the magnitude of the temperature sensitivity (−6 days per degree of warming) agrees with other estimates, including for irrigated vineyards in Australia[12].

Correlations are positive, although weaker, with MJJ precipitation (Fig. 2, middle row) and PDSI (Fig. 2, bottom row), indicating earlier harvests during drought conditions. This may be due to direct drought impacts on fruit maturation by increasing abscisic acid production[12], but is more likely to occur through interactions between soil moisture and air temperature (see 'Temperature versus Moisture Comparisons' and 'Multiple Regression Analyses' in the Supplementary Methods). Dry soils favour sensible over latent (that is, evapotranspiration) heating, increasing soil and air temperatures and speeding up fruit maturation. Western Europe is a region where this soil moisture–temperature interaction is thought to be especially strong[26] (Supplementary Fig. 12, top row). These moisture versus harvest date relationships persist through the middle of the century (1951–1980), but become insignificant in recent decades (1981–2007) (Fig. 3).

To further investigate this apparent weakening of the harvest–drought relationship, we composited climate anomalies back to 1600 during early harvest years, defined as years when GHD-Core was −7.67 days early or earlier (one standard deviation). For this, we used June–July–August (JJA) average climate, the closest match available to the MJJ season in the seasonally resolved climate reconstructions. In the instrumental data, the relationships between GHD-Core and temperature and precipitation weaken during JJA compared to MJJ, whereas PDSI improves slightly (Supplementary Fig. 13). All regressions before 1980 are still significant, however, and JJA comparisons between grape harvest date and moisture (precipitation and PDSI) show a similar weakening and loss of significance from 1981–2007. The temperature–moisture coupling relationships for 1901–1980 are stronger during JJA than MJJ, and both the precipitation and PDSI regressions with temperature also become insignificant afterwards (Supplementary Fig. 14).

Compositing the early harvest dates in GHD-Core yields 72 years from 1600–1980; from 1981–2007, the composite ranged from 11–18 years, depending on the end date of the different climate reconstructions (Fig. 4; sample sizes indicated in this figure, and see Supplementary Methods for full discussion). As expected, early harvests are associated with warmer than average conditions in both intervals, increasing in intensity in the more recent period (consistent with large-scale greenhouse-gas-forced warming trends over Europe). Composite precipitation and PDSI are dry during 1600–1980, with regional average precipitation −11% below normal and mean PDSI = −1.1 (indicative of, on average, modest drought conditions for these early harvests).

After 1980, the association between dry anomalies and early harvests effectively disappears, with regional average mean precipitation only slightly below normal (−1.3%) and PDSI actually wetter than average (+0.86). Differences in the early harvest PDSI composite pre- and post-1980 are highly significant (one-sided Student's t-test, $p \leq 0.001$), whereas only marginally significant for precipitation (one-sided Student's t-test, $p = 0.08$). However, a one-sample Student's t-test comparing the precipitation anomalies against a mean of zero found that only the precipitation anomalies for the early harvests in the pre-1980 period are significantly drier than average. The lack of a significant drought in PDSI or precipitation during early harvests after 1980 was confirmed by a resampling analysis to test for uncertainties in the composite averaging (Supplementary Fig. 15). These results further support our conclusion from the twentieth-century climate analyses, indicating that drought has become decoupled in recent decades as a significant driver of early harvest dates.

Two factors are likely to have contributed to the diminishing importance of moisture for wine grape phenology. The first is the

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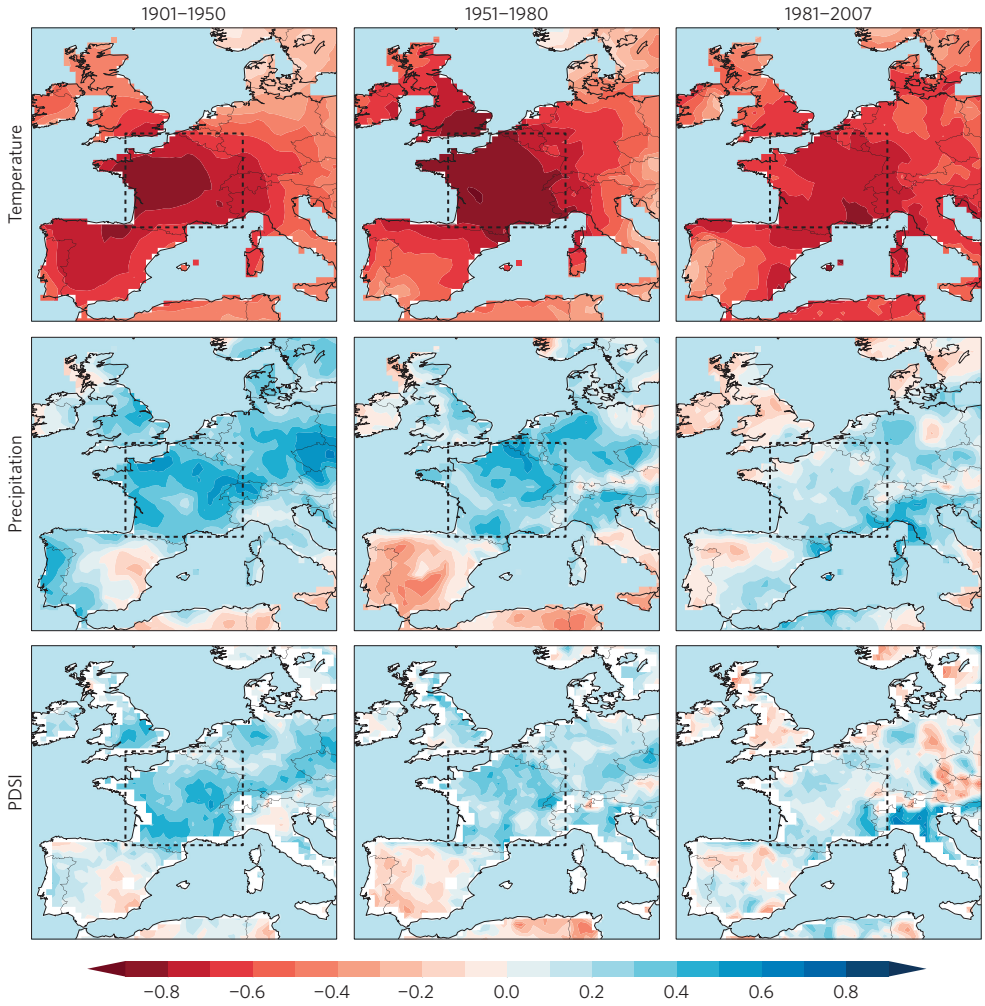

Figure 2 | Twentieth-century analysis between climate observations and GHD-Core. Panels show point-by-point correlations (Spearman's rank) between GHD-Core and May–June–July temperature, precipitation and Palmer Drought Severity Index (PDSI) for three periods: 1901–1950, 1951–1980 and 1981–2007. All the climate data are from the CRU 3.21 climate grids, described in the Methods section. Dashed boxes indicate the region over which climate observations and reconstructions are averaged (2° W–8° E, 43° N–51° N) for regression analyses with GHD-Core.

apparent weakening of the soil moisture–temperature relationship over Western Europe in recent decades, which is especially apparent for JJA (Supplementary Fig. 14). Before 1981, moisture variability (as represented by precipitation and PDSI) accounts for approximately 25% of the year-to-year JJA temperature variability in this region. In more recent decades, however, the moisture–temperature regressions become insignificant. Second, with the strengthening of anthropogenic greenhouse-gas-induced warming, this added heating has made it easier for summers to reach critical heat thresholds needed for early harvest dates. Previously, drought conditions would have been a necessary pre-condition to reach such extremes.

Climate and harvest timing are both thought to affect wine quality, but these relationships are generally assumed to be stationary. If the climatic constraints on wine grape phenology are changing, however, then environmental effects on quality may also be non-stationary. Using wine ratings for the Bordeaux and Burgundy regions[22], we analysed harvest timing and climate effects on wine quality pre- and post-1980. In these regions the likelihood of higher-quality wines increases with earlier harvests and higher temperatures (see Supplementary Table 6), and these harvest date and temperature effects are generally significant and of similar magnitude before and after 1980. Higher-quality wines are also favoured by dry conditions pre-1980 (Supplementary Table 7), but the relationship between PDSI and quality weakens considerably after 1980 (either becoming insignificant or seeing much reduced magnitudes in the ordinal coefficients). Thus, there has been a recent decoupling between wine quality and drought, similar to the results from our climate and grape harvest date analysis.

Our findings—suggesting a large-scale shift in how climate drives early harvests across France and Switzerland—are generally consistent across regions (Supplementary Figs 4–11). This consistency is important for two main reasons. First, wine grape varieties span a great degree of phenological diversity, and there may be related differences in their sensitivities to climate[20] within and across regions[27]. Second, both the trends in harvest dates and changes in the climate constraints could be explained by viticultural management changes in recent decades, rather than shifts in environmental forcing. We find, however, good cross-site correlations across the regional series used to create GHD-Core (Supplementary Table 3 and Supplementary Fig. 3) and diverse regions—for example, Alsace, Champange, Burgundy and Languedoc—show findings similar to our overall results (Supplementary Figs 4–11, one notable exception was Bordeaux, where climate relationships have been relatively stable over time). These regions span greatly differing varieties and management regimes that have generally not shifted similarly, indicating coherency in the climate signal across regions. This makes

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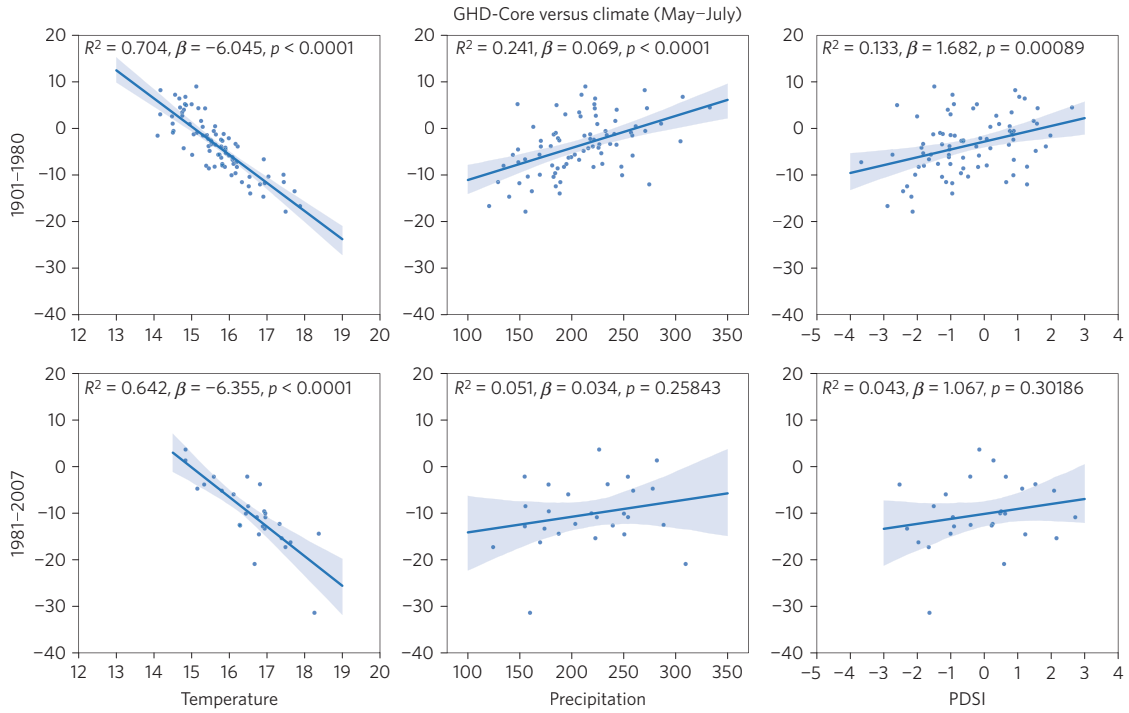

Figure 3 | Twentieth-century analysis between climate observations and GHD-Core. Panels show linear regressions between GHD-Core and May–June–July climate variables from CRU 3.21, averaged over the main GHD-Core region (2° W–8° E, 43° N–51° N). The top row shows results from 1901–1980; the bottom row for 1981–2007. Calculating the regression statistics on the detrended data yielded nearly identical results, summarized in Supplementary Table 8.

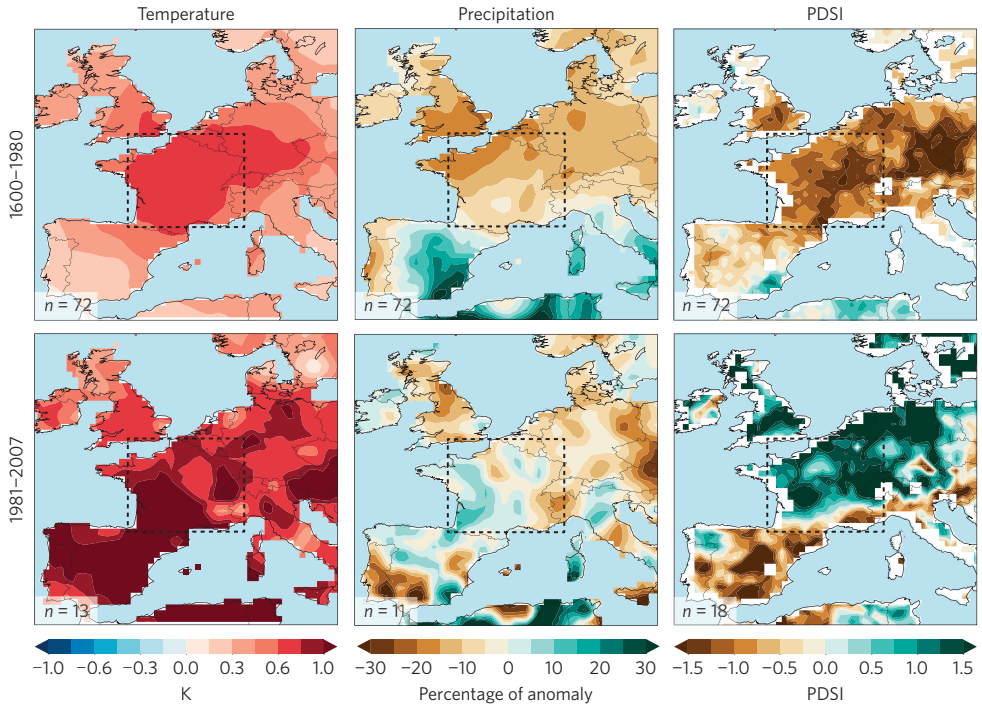

Figure 4 | Analysis between palaeoclimate reconstructions and GHD-Core. Composite average temperature, precipitation and PDSI anomalies from the various climate reconstructions (see Methods) from years with early harvest dates (7.67 days early, or earlier). Numbers in the lower left corners indicate the number of years available to construct each composite average.

it unlikely our results and interpretations are biased by one (or a few) of the grape harvest date series, or by other—non-climatic—viticultural shifts (for example, see *Phylloxera* section of Supplementary Methods). Further, irrigation, the management activity that would be most likely to complicate our climate interpretations, is generally not allowed in France, making it highly unlikely that this could explain the reduction in moisture signal in recent years.

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Our results indicate a fundamental shift in the role of drought and moisture availability as large-scale drivers of harvest timing and wine quality across France and Switzerland. Long-term grape harvest date records and wine quality estimates demonstrate that warm temperatures have been a consistent driver of early harvests and higher-quality wines. Relationships with drought, however, have largely disappeared in recent decades, a consequence of large-scale shifts in the climate system that have decoupled high growing season temperatures from dry summers. Droughts are still likely to affect vine health and development and the wine industry independent of temperature effects, especially in wine-growing regions that are significantly drier than France[12,28]. And our results do not necessarily presage an inevitable future where wine quality is dominated by environmental changes. In reality, grape harvest date and wine quality depend on a number of factors beyond climate—including wine grape varieties, soils, vineyard management, and winemaker practices[29,30]. Our results do suggest, however, that the large-scale climatic drivers within which these generally local factors act has fundamentally shifted. Such information may be critical to wine production as climate change intensifies over the coming decades in France, Switzerland, and other wine-growing regions.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

B.I.C. and E.M.W. conceived of the paper and contributed equally to the writing. B.I.C. conducted the climate analyses and processing of the harvest data, with contributions from E.M.W. E.M.W. performed the wine quality analysis.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.I.C.

Competing financial interests

The authors declare no competing financial interests.

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Methods

Grape harvest data. We analysed harvest data in the database of regional wine grape harvest time series from Western Europe compiled by Daux *et al.* 2012 (hereafter, Daux; ref. 4). Daux included 27 regional composite time series of wine grape harvest dates, compiled from local vineyard and winery records going back as far as 1354. Most of these series were from France, but also included were data from Switzerland, Spain, Luxembourg and Germany (Supplementary Fig. 1). These data were ideal for climate change research applications because management practices have changed relatively little over time (in comparison to other wine-growing regions such as those in North America or Australia) and irrigation as a viticultural tool (which could have complicated the interpretation of climate relationships) was (and still is) largely absent, especially in France. Indeed, these data have been used previously to develop proxy-based temperature reconstructions for the region[4,25].

We created a composite average index from several regional series (GHD-Core) as the focus for our analysis. Using a multi-site composite series had two main advantages. First, every regional grape harvest date series had at least some missing values. By averaging multiple sites into a single composite index, we were able to ensure a serially complete time series back to 1600. Second, because viticulture management varies across wine grape varieties and regions, use of a composite average series should minimize the influence of local management effects (which are unlikely to be synchronous across space) and instead emphasize larger-scale signals related to climate variability and change (the primary focus of our study).

Other analyses of climate change and historical grape harvest dates have attempted to adjust the recorded dates based on sugar levels (for example, Baume and Brix levels, or, relatedly, potential alcohol) in the fruit[12]. This is because management changes designed to select specific sugar levels in the fruit may affect harvest timing; such changes may be independent of climate or may be caused by climate change allowing growers to pick riper grapes[28]. Unfortunately, data on sugar levels are unavailable for the Daux harvest date data set (García de Cortázar-Atuari, personal communication), and the relationship between harvest dates and sugar levels is not consistent across regions or even vineyards[31], making it difficult for us to estimate how sugar levels may have changed our core index. However, we believe lack of this information is unlikely to affect our results. First, the multi-site composite index we constructed, GHD-Core, is designed to maximize the large-scale climate sensitivity and minimize the effects of local management changes. Second, we see similar trends across regions where management for sugar levels have not been similar (Supplementary Figs 4–11), suggesting climate is a far stronger signal than shifts in harvest for particular sugar levels. Next, we note that the harvest date sensitivity to temperature (the primary driver) in GHD-Core has a similar magnitude pre- and post-1980. Shifts in harvest timing to select for higher sugar levels would tend to delay harvest (given no change in climate), thus if these shifts were extreme we would expect the relationship between temperature and harvest date to weaken. As this does not occur, it is likely that any management driven shifts in harvest timing that have occurred have been relatively minor. Finally, we note that the only changing climate relationship is between harvest and drought. There is no a priori reason, however, to expect management shifts in harvest to change this relationship, while maintaining a significant relationship with the primary harvest driver (temperature).

From the 27 regional grape harvest date series available, we chose eight sites (Supplementary Table 1) to construct GHD-Core: Alsace (Als), Bordeaux (Bor), Burgundy (Bur), Champagne 1 (Cha1), Languedoc (Lan), Lower Loire Valley (LLV), Southern Rhone Valley (SRv), and Switzerland at Leman Lake (SWi). All seven regional series were over 80% serially complete back to 1800, and all but Cha1 and LLV were over 60% complete back to 1600 (Supplementary Table 2). Importantly, all eight sites had good coverage for the most recent period (1981–2007) when we conclude that drought controls on harvest date have significantly weakened. After 1600, most years have at least 3–4 of these regional series represented; sample depth declines sharply before this date (Supplementary Fig. 2). All analyses are thus restricted to the period from 1600–2007, which is also the time period indicated by Daux as the most reliable.

Before compositing, we converted each harvest date series to days per year anomaly, relative to their local mean for 1600–1900. Despite the broad geographic range and climates gradients covered by these sites, there was good cross-site correlation in the harvest dates (Supplementary Table 3 and Supplementary Fig. 3). Average harvest dates for all regional series, as well as GHD-Core and GHD-All (a composite average of all 27 sites), were anomalously early during the recent 1981–2007 interval relative to the baseline averaging period of 1600–1900, ranging from on average −2 days (Cha1) to over −23 days (SWi) early (Supplementary Table 4). There were also small differences across time in the inter-annual standard deviation in harvest dates (Supplementary Table 5), with most sites showing slightly reduced variability during the twentieth century compared to 1600–1900.

Climate data and reconstructions. Instrumental temperature and precipitation data for the twentieth century (1901–2012) were taken from version 3.21 of the CRU climate grids[21]. These data were monthly gridded fields, interpolated over land from individual station observations to a spatially uniform half-degree grid. We also used a drought index, an updated version of the Palmer Drought Severity Index (PDSI; ref. 32) derived from the CRU data[33]. PDSI is a locally standardized indicator of soil moisture, calculated from inputs of precipitation and evapotranspiration. PDSI integrates precipitation over multiple months and seasons (about 12 months), and so it incorporates longer-term changes in moisture balance beyond the immediate months or season.

To extend our analysis further back in time, we also used three largely independent proxy-based reconstructions of temperature[5], precipitation[7] and PDSI (ref. 6). The temperature and precipitation products are three-month seasonal reconstructions (DJF, MAM, JJA, SON) using primarily historical documentary evidence over the past 500 years. The temperature reconstruction covers the period 1500–2002; the precipitation reconstruction covers 1500–2000. The PDSI reconstruction is summer season only (JJA) and is based entirely on tree ring chronologies distributed across Europe. It covers the entire Common Era, up through 2012. Before comparisons with the grape harvest data, we anomalized all three reconstruction products to a zero mean over 1600–1900, the same baseline period used in the harvest date anomaly calculations.

Wine quality data and analyses. We extracted wine quality data from Broadbent 2002[22], which was ideal for our analyses in that it represented quality assessed by a single observer, who also attempted to correct for 'age since vintage' in his ratings. Ratings were scaled from 0 to 5, with 0 indicating a 'poor' vintage and 5 indicating an 'outstanding' vintage. We extracted data for the 1900–2001 vintages in Bordeaux and Burgundy (2001 being the last year of data in the book). We selected these two regions for analysis because they are two of France's major wine-growing regions, coinciding with two major time series of grape harvest date included in GHD-Core, and represented the most serially complete time series (99% for red Bordeaux, 98% for white Bordeaux, 88% for Red Burgundy and 59% for white Burgundy, with almost all the missing data occurring before 1950). We fit ordered logit models to wine quality and CRU 3.21 climate data for each region by wine colour (red or white), using the package ordinal in R 3.1.2 (ref. 34).

Data availability. All data are publicly available from the NOAA Palaeoclimate Archive: https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets. All Python code (Python Notebooks) used in the analyses is available from: https://github.com/bcook/WINENCC.

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