Climate change decouples drought from early wine grape harvests in France

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Winegrape phenology has significantly advanced in recent decades[1–3], likely in response to climate change induced trends in temperature and drought, the main drivers of fruit maturation. Fully understanding climate change contributions to these trends, however, requires analyzing winegrape 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 early grape harvest dates (GHD) from 1600–2007 in France, using historical GHD data[4] and independent reconstructions of temperature[5] and drought[6,7]. We demonstrate that warm temperatures and drought during the late spring and early summer (May-June-July) are the primary drivers of early harvests, but that in recent decades (1981–2007) drought has become decoupled from harvest timing. 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, with enhanced warming from

anthropogenic greenhouse gases, sufficiently high temperatures for early harvests can now occur regularly without drought. Our results suggest that anthropogenic climate change may have fundamentally altered the climatic drivers of early winegrape harvests in France, with possible ramifications for viticulture management and wine quality.

Winegrapes (*Vitis vinifera* ssp. *vinifera*) are the world's most valuable horticultural crop, and there is increasing evidence that warming trends have advanced winegrape harvest dates in recent decades[1,2,8–12]. Harvest dates are closely connected to the timing of grape maturation which is, in turn, highly sensitive to climate during the growing season. Specifically, warmer temperatures accelerate grape vine phenological development from flowering to fruit maturation and harvest, while increased precipitation tends to delay winegrape 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 regions[8,14], and are also favored by warm summers with above average early-season rainfall and late season drought. This ensures the vines and grapes 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], though temperature is suggested to be most critical to winegrape phenology[14,19].

While the effects of climate (temperature[14,19] and moisture[18]) on wine quality and grape harvest dates[11,12] (GHD) have been widely studied in recent years, most have focused on relatively short, recent timescales (e.g., 30–40 years[1,10,12]). There has thus been little consideration of the 1) longer term historical context of recent GHD trends and 2) possible non-stationarities in the relationship between winegrape phenology and climate. We address these issues by conducting a new analysis using over 400 years (1600–2007) of GHD data from Western Europe[4]. From this database, we construct a multi-site GHD index (hereafter, GHD-Core) by averaging harvest date anomalies from 8 regional GHD time series across France and Switzerland (see Methods for more details). We then analyze the variability and trends in GHD-Core, and compare against instrumental climate data over the 20th century[20] and proxy-based reconstructions of temperature[5], precipitation[7], and soil moisture (Palmer Drought Severity Index; PDSI)[6] (PDSI) back to 1600.

The GHD-Core series has pronounced variability from year to year and a strong trend towards earlier dates in the latter part of 20th century (Figure 1). The latest date in the record (Figure 1, left panel) is 1816, the so called 'Year without a Summer' following the eruption of Mount Tambora in Indonesia[21]. 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 date in the record is 2003 (-31.4 days), coinciding with one of the worst summer heat waves in recent history[22]. Mean harvest dates were modestly early during the first half of the 20th century (1901–1950, -5.2 days), roughly average from 1951–1980 (-1.1 days), and substantially earlier during the most recent decades (1981–2007, -10.24 days) (Supplemental Table 4). Notably, the 1981–2007 dates exceed one full standard deviation of GHD variability calculated from the baseline averaging period (1600–1900, ± 7.67 days) and are significantly earlier than 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 interval (1635–1661, -7.42 days), although results are only marginally significant (One Sided Student's t-test, $p = 0.075$).

There are strong and significant correlations between GHD-Core and the instrumental climate data, although the strength of the moisture relationships (precipitation and PDSI) declines in recent years (Figure 2) (for regional GHD series, see Supplemental Figures 4–11). GHD-Core correlates negatively (Spearman's rank) with May-June-July (MJJ) temperatures across Western Europe (Figure 2, top row), indicating a strong tendency for earlier harvests during warmer conditions in late spring and early summer. Regional average (dashed box in Figure 2; 2°W–8°E, 43°N–51°N) MJJ temperatures are the single best predictor of GHD-Core (Figure 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 (-6 days per degree of warming), suggesting that the temperature sensitivity of harvest dates is relatively stationary.

Correlations are positive, though weaker, with MJJ precipitation (Figure 2, middle row) and PDSI (Figure 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] or indirectly through feedbacks between soil moisture and air temperature. Dry soils favor sensible over latent (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[23] (Supplemental Figure 12, top row). These moisture-GHD relationships persist through the middle of the century (1951–1980), but become insignificant in recent decades (1981-2007) (Figure 3).

To investigate further, 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 exercise, 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, while PDSI improves slight (Supplemental Figure 13). All regressions prior to 1980 are still significant, however, and JJA comparisons between GHD and moisture (precipitation and PDSI) show a similar weakening and loss of significance from 1981–2007. Notably, the temperature-moisture coupling relationships improved for the 1901–1980 period, becoming insignificant afterward (Supplemental Figure 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 (Figure 4). 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 precipitation averaging -11% below normal and mean PDSI=-1.1 (indicative of a modest drought).

After 1980, the typical dry anomalies associated with early harvests effectively disappear, with 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, $p \leq 0.001$), while 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 in the pre-1980 period are significantly below normal. These results were confirmed by a Monte-Carlo analysis to test for sampling uncertainties in the composite averaging (Supplemental Figure 15). These results further support our conclusion from the 20$^{\text{th}}$ century climate analysis, indicating that drought has become decoupled in recent decades as a significant driver of early harvest dates.

Two things have likely contributed to the diminishing importance of moisture for winegrape phenology. The first is the apparent weakening of the soil moisture-temperature relationship over Western Europe in recent decades, which is especially apparent for JJA (Supplemental Figure 14). Prior to 1981, moisture variability (as represented by precipitation and PDSI) accounts for approximately 25% of the year to year temperature variability in this region. In more recent decades, however, these 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 if the climatic constraints on winegrape phenology are changing, then these environmental effects on quality may also be non-stationary. Using wine ratings for the Bordeaux and Burgundy regions[24], we analyzed 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 Supplemental Table 6), and the harvest date and temperature effects on quality are significant and of similar magnitude before and after 1980. Higher quality wines are also favored by dry conditions pre-1980 (Supplemental Table 7), but the relationship between moisture and quality weakens considerably after 1980 (either becoming insignificant or seeing much reduced magnitudes in the ordinal coefficients). There has thus been a recent decoupling between wine quality and drought, similar to the results from our climate and GHD analysis.

Our interpretations of the climate signals in GHD-Core harvest dates are tempered by two main caveats. Firstly, winegrape varietals are not monolithic and there may be significant differences in their sensitivities to climate within and across regions[25]. Second, both the trends in harvest dates and changes in the climate constraints may be explained by management changes in recent decades, rather than shifts in environmental forcing. Among the regional series used to create GHD-Core, however, we find good cross-site correlations (Supplemental Table 3; Supplemental Figure 3) and consistent climate response (Supplemental Figures 4–11). This indicates some commonality to the climate signal across the regions, making it unlikely our results and interpretations are biased by one (or a few) of the GHD series. We also note that focusing on a multi-site series, like GHD-Core, is likely to minimize the influence of management changes, which are not likely to highly local in character and not synchronous across regions. Finally, we note that irrigation, the management activity that would be most likely to complicate our climate interpretations, is largely *interdit* (forbidden) in France, making it highly unlikely that this could explain the reduction in moisture signal in recent years.

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. Long-term GHD records and wine quality estimates demonstrate that warm temperatures have been a consistent driver of early harvests and higher quality wines, but relationships with drought 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. Importantly, our results do not presage an inevitable future where wine quality is dominated by environmental changes. In reality, wine quality depends on a variety of factors beyond climate, including terroir, vineyard management, and winemaker practices. However, our results suggest the climatic contributions to GHD and wine quality are shifting, and that this information should be considered as climate change intensifies over the coming decades in France and other wine growing regions.

Methods

Grape Harvest Data. We analyzed GHD data in the database of regional winegrape harvest time series from Western Europe compiled by Daux et al 2012 (hereafter, DAUX[4]). DAUX included 27 regional composite time series of winegrape 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 (Supplemental Figure 1). These data were ideal for climate change research applications because management practices have changed very little over time and irrigation as a viticulture 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].

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 GHD 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 winegrape varietals 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).

From the 27 regional GHD series available, we chose 8 sites (Supplemental Table 1) to construct GHD-Core: Alsace (Als), Bordeaux (Bor), Burgundy (Bur), Champagne 1 (Cha1), Languedoc (Lan), the Lower Loire Valley (LLV), the Southern Rhone Valley (SRv), and Switzerland at Leman Lake (Swi). All 7 regional series were over 80% serially complete back to 1800 and all but one (Cha1) were over 60% complete back to 1600 (Supplemental Table 2). Importantly, all 8 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 prior to this date (Supplemental Figure 2). All analyses are thus restricted to the period from 1600–2007 (also the time period indicated by Daux et al 2012 as the most reliable).

Prior to compositing, we converted each GHD 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 (Supplemental Table

3; Supplemental Figure 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 day (SWi) early (Supplemental Table 4). There were also small differences across time in the inter-annual standard deviation in harvest dates (Supplemental 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[20]. 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[26]) derived from the CRU data[27]. 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[6]. The temperature and precipitation products are 3-month seasonal reconstructions (DJF, MAM, JJA, SON) using primarily historical documentary evidence over the last 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 upon tree ring chronologies distributed across

Europe. It covers the entire Common Era, up through 2012. Prior to comparisons with the GHD data, we anomalized all three reconstruction products to a zero mean over 1600–1900, the same baseline period used in the GHD data.

Wine Quality Data & Analyses. We extracted wine quality data from Broadbent (2002)[24], which was ideal for our analyses in that it represented quality assessed by 1) a single observer who 2) 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 vintages 1900-2001 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 GHD 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 of the all the missing data occurring before 1950). We fit ordered logit models for each region by wine color (red or white), using the package `ordinal` in `R`[28].

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Figure 1 Time series of Grape Harvest Date (GHD) anomalies from GHD-Core (left panel), composited from the Als, Bor, Bur, Cha1, Lan, LLV, SRv, and SWi regional GHD time series in the DAUX dataset. All anomalies are in units of day of year anomalies, calculated relative to the average date from 1600–1900. In the right panel, we compare normalized histograms of GHD anomalies from GHD-Core for two periods: 1600–1980 and 1981–2007.

Figure 2 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.

Figure 3 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 Supplemental Table 8.

Figure 4 Composite average temperature, precipitation, and PDSI anomalies from the various climate reconstructions (see Methods) from years with early harvest dates (≤ -7.67 days early). Numbers in the lower left corners indicate the number of years used to construct each composite.