Science of the Total Environment 685 (2019) 508–513

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Short Communication

Precipitation intensity under a warming climate is threatening some Italian premium wines

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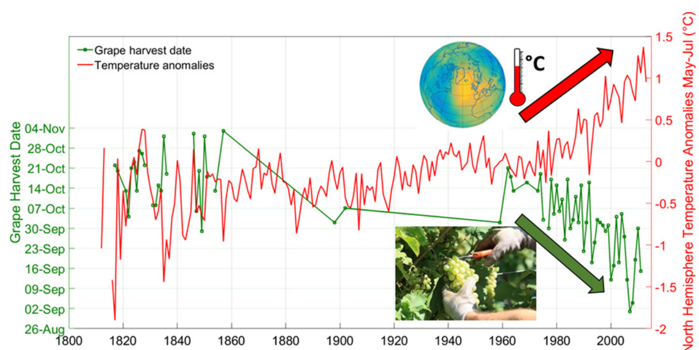
HIGHLIGHTS

- Global warming is recorded also locally and is impacting grapevine phenology.
- Harvest date of premium wine analysed with local meteorological data shows the role of climate change.
- Increase of Precipitation intensity exacerbate the influence of the temperature rise on grapevine.
- Short intense precipitations are not beneficial for grapevine.
- Keeping the high quality of wine using unchanged cultivation technique is becoming harder.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 March 2019
Received in revised form 27 May 2019
Accepted 29 May 2019
Available online 30 May 2019

Editor: Elena Paoletti

Keywords:
Climate change
Precipitation
Temperature
Phenology
Grape harvest date
CO_2

ABSTRACT

Changes in regional climate are causing disruptions in global agriculture, including wineries that produce premium wines. Temperature is the key factor influencing the growth stages of wine grapes worldwide and its recent increase is causing early harvests, affecting the quality and quantity of premium wine. Water availability is the other important element: during the growing season the crop yield benefits of constant moderate rains, whereas this positive effect would be reversed if the same precipitation amounts fell in short periods of time. Climate change may alter the characteristics of precipitation such as intensity, duration and frequency of rain even if it does not alter the total amount of precipitation. Although the impact of precipitation amount and drought on wine grape phenology have been investigated, knowledge of the role of precipitation characteristics is very limited. Here we show that the precipitation intensity, which is the precipitation amount divided by the number of the rainy days (NRD), has also caused early grape harvest dates for one grape varietal. Using the harvest dates (1820–2012) of a premium wine made by a winery that has kept the cultivation methods and practices unchanged since 1650, we found that for growing seasons since 1960, annual harvest dates have been getting early as temperature increases (−5.92 days $°C^{-1}$) and more intense precipitation events occur (−1.51 days/(mm/NRD)). Our results are consistent with the hypothesis that the increasing tendency of precipitation intensity could exacerbate the effect of global warming on some premium wines that have been produced for >400 years.

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https://doi.org/10.1016/j.scitotenv.2019.05.449
0048-9697/

1. Introduction

The wine industry has had cultural and economic importance in Europe for centuries and now may be threatened by climate change (Cook and Wolkovich, 2016; Fu et al., 2014; Sherry et al., 2007; Cleland et al., 2007). Europe is the largest global producer, with 56.3% of the total in 2017, and Italy produces more wine than any other country, accounting for >30% of the European volume (EU Wine Market Data Portal, 2018). In the past fifteen years, European wine production has shifted from cask and low-cost bottle wine toward premium wines, with 82% of the EU wine grape area now used in quality, premium wines (Agriculture, forestry and fishery statistics, 2017). In Italy, as well as other wine-growing countries, premium wines have been produced for centuries. Several studies have shown that premium wine production and climate are linked (White et al., 2006; Jones et al., 2005).

Premium wines can provide a good indicator of climate change for several reasons. First, the premium wine grapes are sensitive to climate changes, requiring a narrow climate range that excludes both extreme heat and extreme cold (White et al., 2006). Second, some premium wines have been produced the same way in the same location for centuries (White et al., 2006; Chuine et al., 2004). Third, some vintners have kept long-term records of annual wine production (Meier et al., 2007; Jones and Davis, 2000). One of the most well-documented aspect of premium wine production is the grape harvest date (GHD), which is tightly linked to grape maturation (Meier et al., 2007; Sun et al., 2018). The strong connection between GHD and temperature serves as a proxy to reconstruct past climate (Meier et al., 2007; Sun et al., 2018) as well as a predictor of the impact of climate change on wine quality and a guide for adapting wine production to a warmer climate (White et al., 2006; Wolkovich et al., 2018). Early GHD is always associated with temperature increases during the growing season, whereas more precipitation, in terms of the total amount of rain or the average rain measured in a certain period, generally delay harvest (Cook and Wolkovich, 2016; Fu et al., 2014; Sun et al., 2018). Thus precipitation must be considered as well as temperature when analysing these long-term records of a premium wine GHD (Ciais, 2005). Although the impact of precipitation amount and drought on wine grape phenology have been investigated, knowledge of the role of precipitation characteristics is very limited (Cook and Wolkovich, 2016; Wolkovich et al., 2018).

Precipitation can be characterized for a growing season as total amount of rainfall, number of the rainy days (NRD), which is the number of days with precipitation equal or above 1 mm, or precipitation intensity, which is the total amount of precipitation divided by the NRD. These characteristics can vary from region to region and can respond differently to climate change (Allan and Soden, 2008; IPCC, 2013; Trenberth, 2011; Giorgi et al., 2014). However, there is a general consensus that the annual precipitation (mm/yr) has changed little or not at all for 76% of the global land surface (IPCC, 2013; Trenberth, 2011). In contrast, observations confirm that the number of heavy precipitation events has increased over much of the global land surface (Fischer and Knutti, 2016; Trenberth, 2011; Hannah et al., 2013; van den Besselaar et al., 2013). Model simulations for future scenarios of global warming predict that heavy precipitation events will become more frequent and more intense (Donat et al., 2016; Trenberth, 2011; Giorgi et al., 2014; Rajczak and Schär, 2017). Severe precipitation causes flooding, landslides, agricultural damage and loss, including vineyard damage and loss.

Several previous studies of the relationship between climate and wine production have used multiple grape varietals. However, each varietal can have different quality standards, resulting in grape harvest dates at different levels of maturation from year to year, and a different response to climate stresses. In addition, over the years, many vineyards have changed their cultivation techniques, such as using irrigation and fertilizers, and these changes could alter the GHD (Webb et al., 2012; Thorne and Vose, 2010). Finally, some of these studies use global meteorological data, which may not accurately represent the climate at the vineyards (Thorne and Vose, 2010). All of these issues can mask a possible correlation between GHD and climate change. We address these issues by analysing the GHD of a premium white wine (Trebbiano d'Abruzzo) from a single vineyard. This wine won the best wine of Italy award in 2012 (Xoplaki et al., 2003) and has been constantly ranked in the top 10 of Italian wines for the past decade. The winery has used the same cultivation practices since 1650, with no irrigation or fertilization, and has a long-term record of GHD. As a result, it should be possible to determine the climate sensitivity of the GHD for this wine without biases due to changes in cultivation practices or grape varietals. The goal of this work is to explore if the advance of the recorded GHD is triggered by the observed changes of climatological parameters. In particular which of the different meteorological parameters and climatological indexes can be used to describe the GHD changes. Considering the observed and predicted increase for the future of severe precipitation events, we introduce another parameter (precipitation intensity) among those usually considered to drive GHD, to assess if this characteristic of precipitation plays a role in the advance of GHD.

2. Materials and methods

2.1. Data sources

The GHD data come from the winery records, which date back to 1818, although two multi-decadal gaps occur in the mid-to-late 1800's and the early-to-mid 1900's, but cover every year since 1959 (Fig. 1). The gap from 1840 to 1880 was due to the political instability caused by the Italian unification; the gap in the 1900's was due to the First and Second World Wars. Valentini's family that has run the winery since 1650 did not record the GHD prior to 1820. Documents at the winery attest that the vinicultural and wine-making practices have not changed since 1650. In detail, the Valentini vinery is still keeping the grape harvesting following the procedure used for centuries: 1) grape are picked by hands, without the assistance of machinery; 2) the harvest timing is not impacted by irrigation, which is a practice never used in this vinery. The identification of the maturation time of wine grape has not been changed along the centuries and is still the same nowadays, including: analysis of some changes in different berries characteristics such as skin color, skin thickness, softness; to check if the pulp is still attached to the grape seed and, finally, the berry tasting. In the last decades with the availability of instruments to quantify characteristics of berry such as sugar and acidity, measurements of these parameters have been done only as a validation of the traditional method used; 3) chemical fertilizations have never been used neither in the present nor in the past centuries. The only practice, used to protect barriers from fungi, kept as similar as possible to what generally used since middle '800, is to spray grapes with copper and sulfur-based fungicide. Temperature and precipitation parameters are local data observed near the winery by a meteorological station of the National Hydrographic Service (NHS), now Centro Funzionale of Abruzzo Region (Italy), defining the local climatology, whereas GPH, NAO and EAP describe the large-scale climate variability. The meteorological station of the NHS, is located at about 5 km from the vinery and at the same mean altitude of the vineyard. The meteorological data were validated and homogenized to take into account possible brakes and interferences due to changes of the detector, human errors (for data of the period when the instrument was analog), and any other sort of errors. The technique applied to reduce the impact of these errors is the homogenization, which is generally used for long-term climatological data. The homogenization software used is HOMER and more details can be found in Aruffo and Di Carlo (2019).

The North Hemisphere temperature anomalies are retrieved from the Berkeley Earth Surface Temperature analysis (BEST, 2019). This analysis uses a large collection of weather monitoring stations to produce an estimate of the underlying global temperature field across all of the Earth's land surface. The North Atlantic Oscillation (NAO) data

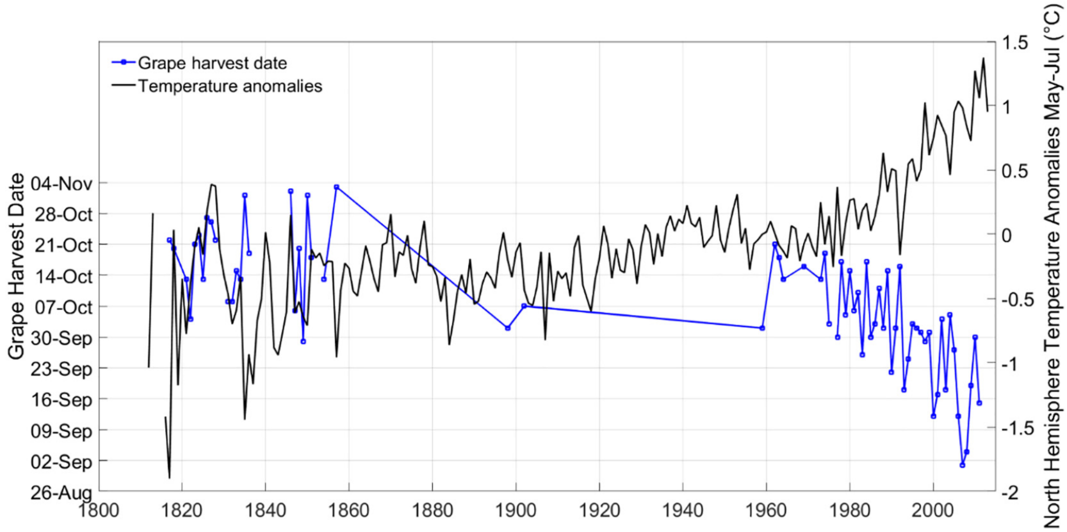

Fig. 1. Grape Harvest Date (GHD) and temperature. Time series of GHD of the white wine recorded in the Valentini's vinery producing premium wines and that of temperature anomalies observed in the North Hemisphere during the growing season (May-Jul).

are from the US National Oceanic and Atmospheric Administration (NOAA) database (NOAA, 2019); the Palmer Drought Severity Index (PDSI) is from a US National Center for Atmospheric Research (NCAR) database (Dai, 2017). The Geopotential Height (GPH), East Atlantic Pattern (EAP), Precipitation Concentration Index (PCI) and Soil Moisture (SOI) are downloaded from the US NOAA/National Weather Service National Centers for Environmental Prediction (NCEP, 2019). All the local and global climatological parameters considered in this analysis are the annual average of the observations made during the period May-Jul that is the growing season for wine grape in Central Italy.

2.2. Data analysis

The first step in the analysis was to find the correlation coefficients and statistical significance for the GHD with all the climatology data from 1959 to 2012 (Table 1), and then the GHD sensitivity to climate parameters was tested with a multivariate regression analysis. The trend of GHD with temperature was −5.92 days $^{o}C^{-1}$. In the period 1820–1959, the GHD trend with temperature was only −0.926 days $°C^{-1}$, but with poor coefficient of correlation and statistical significance ($r = -0.048$ $p = 0.813$). No further analysis can be done with the pre-1959 GHD data.

Climatological parameters showing a correlation with GHD with statistical significance better than 95% ($p < 0.05$) were then used as inputs of the multivariate regression model. As expected, all the temperature data (daily average, maximum and minimum and North Hemisphere anomalies) have high correlation coefficients, but the monthly average of daily maximum has the highest correlation coefficient and, thus, was used to represent temperature in the multivariate regression analysis. This multivariate regression analysis identified that temperature and precipitation intensity in rainy days are the only two parameters with sufficient statistical significance (Table 2). The regression model describes the GHD variation with a Root Mean Squared Error of 7.57, and R-squared of 0.666, F-statistic vs. constant model of 14.8, and p-value = $5.69 \cdot 10^{-08}$.

As a test of this result, a stepwise regression analysis, which uses the Akaike and the increase of R^2 as criteria to add or remove predictors, confirmed that only temperature and precipitation intensity are the drivers of GHD, with a Root Mean Squared Error of 7.38, R-squared: 0.666, F-statistic vs. constant model of 25.9 and p-value = 2.22e-09 (Table 3).

For this winery's red wine, the GHD was recorded in 1900 but then not again until 1958, when annual records have been kept. The time series of the GHD and the North Hemisphere temperature anomalies show the GHD getting early as the temperature gets higher (Fig. S1). The analysis of the GHD and climate variables for the red wine followed the same methodology used for the white wine (Table S1). Unlike for the white wine, precipitation intensity and EAP do not have $p < 0.05$, which is the level of significance used for inclusion of a parameter in the multivariate regression analysis of the white wine GHD (Fig. S2). However, we decided to run the multivariate regression model with the same parameters identified for the white wine in order to have a direct comparison of their effects on the GHD.

The results of the multivariate regression analysis identified temperature with sufficient statistical significance, whereas precipitation intensity shows a statistical significance only slightly above the threshold of 0.05. (Table S2). The multivariate regression model

Table 1
Statistical analysis of GHD of white wine vs meteorological parameters. Coefficients of correlation (r) between the GHD of the white wine and different climate data, including the p-values of the growing season (May – Jul).

GHD vs	r	p
Local precipitation	−0.074	0.643
Local of rainy day	0.238	0.125
Precipitation Intensity (Local precipitation/Local No. of rainy day)	−0.320	0.036
Local daily maximum Temperature	−0.780	$7.327e^{-10}$
Local daily minimum Temperature	−0.705	$1.332e^{-07}$
Local daily averaged Temperature	−0.776	$1.004e^{-09}$
PDSI	−0.264	0.087
EAP	−0.387	0.010
PCI	−0.254	0.105
SOI	0.126	0.427
GPH 500 mb	−0.623	$8.259e^{-06}$
NAO	0.356	0.019
North Hemisphere Temperature Anomalies	−0.678	$5.765e^{-07}$

Table 2
Results of the multivariate regression analysis. Estimation of GHD of the white wine using 5 climate parameters identified with the correlation analysis.

Input data	Estimate coefficient	SE	tStat	p-value
Temperature	5.399	1.383	−3.904	0.000386
Precipitation Intensity	−1.028	0.513	−2.003	0.052
GPH	0.029	0.114	0.258	0.798
NAO	3.578	2.166	1.652	0.107
EAP	−0.482	2.710	−0.178	0.859

Table 3
Results of the stepwise analysis. Statistical results of the stepwise analysis of the GHD of white wine. The parameters identified are only 2, of the 5 used in input.

Parameter identified by the stepwise	Estimate Coefficient	SE	tStat	p-value
Temperature	5.179	0.762	−6.789	$4.173e^{-08}$
Precipitation Intensity	0.992	0.458	−2.165	0.036

describes the GHD variation with a Root Mean Squared Error of 7.04, and R-squared of 0.57, F-statistic vs. constant model of 7.73 and p-value $= 2.45 \cdot 10^{-05}$. The stepwise regression analysis, using the Akaike and increase of R^2 as criterions to add or remove predictors, confirmed that only temperature is the driver of GHD, with a Root Mean Squared Error of 6.81, R-squared: 0.539, F-statistic vs. constant model of 46.8 and p-value $= 3.13e^{-08}$ (Table S3).

3. Results

The link between GHD and climate parameters, in our results, is evaluated for a single wine grape varietal to minimise possible different response of plants to climate stress and with local meteorological data to reduce the effect of data not representative of the local state. Prior to 1980, there is not a clear trend; the GHD ranges between the 2nd of November (the absolute latest GHD on 1846) and the 30th of September, whereas after 1980, the GHD record shows a trend strongly decreasing toward the beginning of September with variations between the 14th of October and the 1st of September (absolute earliest GHD in 2007) (Fig. 1). The sensitivity of GHD to temperature is evident. Temperature was almost constant from 1818 to 1980 (increase of 0.0051 ± 0.0009 °C/year, coefficient of correlation: $r = 0.72$ and 95% confidence bounds), as was the GHD (−0.0512 ± 0.049 day/year, $r = -0.34$ and 95% confidence bounds). After 1980, temperature rose abruptly (0.0323 ± 0.0075 °C/year, $r = 0.84$ and 95% confidence bounds) while the GHD decreased (−0.8237 ± 0.3524 day/year, $r = -0.66$ and 95% confidence bounds).

Among the 13 analysed climate data (Table 1), only 5 showed a correlation with the GHD with sufficient statistical significance to be used as input of the multiple regression model: temperature ($r = -0.78$, $p < 0.001$), precipitation intensity ($r = -0.32$, $p < 0.05$), GPH, ($r = 0.62$, $p < 0.001$), NAO ($r = 0.36$, $p < 0.05$) and EAP ($r = -0.39$, $p = 0.01$) (Fig. 2). Our results show that neither the total amount of precipitation, which was observed with a no trend in the period 1960–2013 at the meteorological station near to the winery despite the increase in precipitation intensity (Fig. 3), nor the NRD play a role in the GHD changes. It is expected that some large-scale climate parameters depict the same meteorological and/or climate conditions described by local quantities (http://biwawards.it/en/classifica-2012/, 2012). For instance, increased local temperature is linked to high pressure over Southern Europe and to the EAP, for which a positive phase is associated with above-average European temperature, and to the NAO, for which a positive value is associated with above-average temperature (Hurrell, 1995). As expected local meteorological data, giving a more representative picture of the climate that affect the growing of the grapevine, are more statistically relevant in the harvest date advance description than large-scale atmospheric parameters. However, when local weather data are not available teleconnection patterns and large-scale meteorological data are valuable to study the connection between climate and GHD (Cook and Wolkovich, 2016). The GHD sensitivity to climate parameters was tested with a multivariate regression analysis. GHD correlates with several locally recorded growing season parameters: temperature, total precipitation, NRD and precipitation intensity. It also correlates with several model-derived parameters: mean temperature of the Northern Hemisphere, the Palmer Drought Severity Index (PDSI), the North Atlantic Oscillation (NAO), the Geopotential Height (GPH), the East Atlantic Pattern (EAP), the Precipitation Concentration Index (PCI) and Soil Moisture (SOI). The sensitivity of GHD to each climate parameter was retrieved with a multivariate linear regression model constrained with those parameters that individually correlated with GHD at a statistical level of significance at least of 95% ($p < 0.05$). A combination of these more significant parameters was used to construct a linear model. The addition and removal of parameters can be based on various criteria and, in our case, were based on two different of them: increase of R^2 and Akaike. To test the results of this analysis, we developed an additional multivariate linear regression model using the stepwise technique that starts the model with a constant value, adds an observed parameter at each iteration (forward phase) and, then, eliminates those with the weakest correlation (backward phase). The result is the final model. The multivariate linear regression analysis of GHD, using the identified observed parameters, shows that only temperature and precipitation intensity are significant, with a level of confidence of $p < 0.001$ and $p < 0.05$ respectively, whereas GPH, NAO and EAP are redundant and insignificant (see Material and Methods).

The same winery produces also a premium red wine (Montepulciano d'Abruzzo), whose grapes are cultivated with the same technique as the white wine and with unchanged practices since 1650. For wineries that have used the same cultivation practices for centuries, the grapes are harvested when they have achieved the right pH and acidity required to produce a premium wine. The desired pH and acidity varies depending on the grape varietal. The trend in the GHD is slightly smaller for the red wine grape (−4.80 days °C^{-1}) than it is for the white wine grape (Fig. S2). The multivariate linear regression and the stepwise regression identified only temperature as a statistically significant driver for the red wine grape, whereas the correlation with precipitation intensity had little statistical significance (see Material and Methods). Compared to the GHD of the white wine grape, the GHD for the red wine has less dependence on temperature and statistically lower dependence on precipitation intensity because the red wine

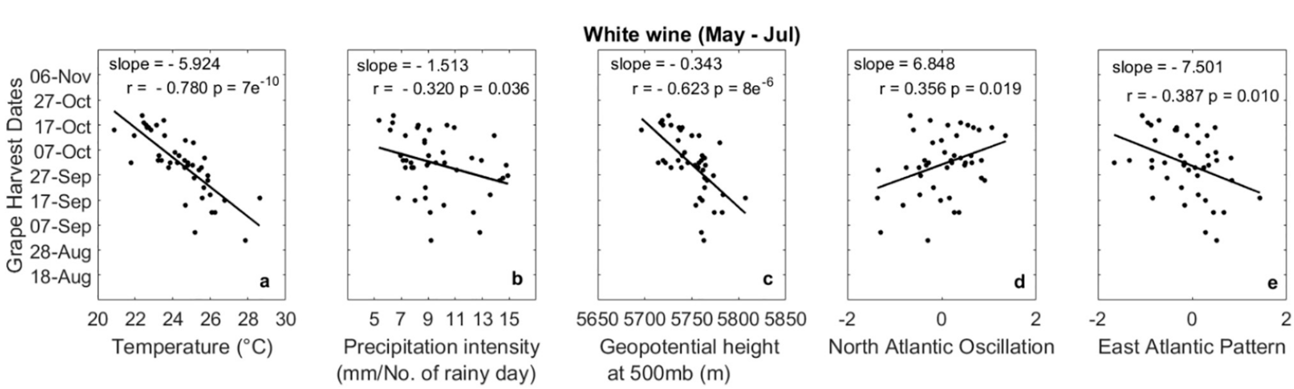

Fig. 2. GHD vs meteorological parameters during the growing season (May-Jul). Linear regression between GHD and: temperature (panel a) and precipitation intensity (panel b) observed close to the vinery, and GPH at 500 mb (panel c), NOA (panel d) and EAP (panel e).

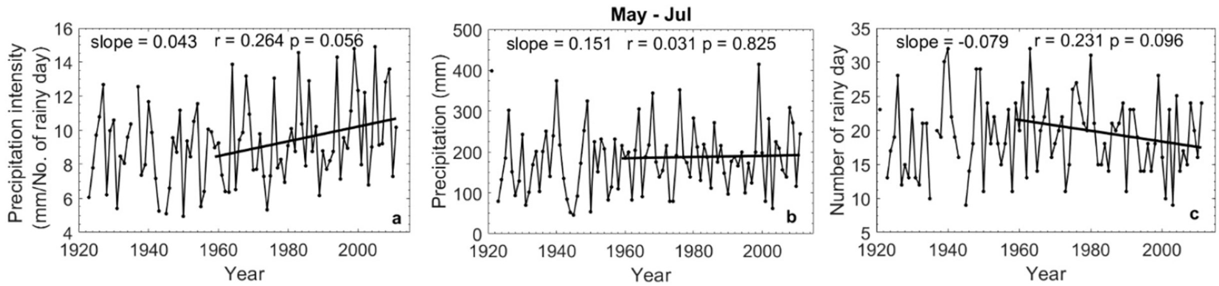

Fig. 3. Observed precipitation character during the growing season (May-Jul). Time series of the observed precipitation intensity close to the vinery during rainy days (panel a), total amount of precipitation (panel b) and number of rainy days (precipitation equal or above 1 mm) (panel c).

grape is more tolerant to heat and drought (Wolkovich et al., 2018). Further, to produce a premium red wine, the red wine grapes must be picked when the grapes have less acidity than is required for the premium white wine. This lower acidity is usually achieved during drier and hotter conditions than are optimum for white wine grape (Wolkovich et al., 2018; Orduna, 2010).

4. Discussion

Using the harvest dates and the multivariate regression analysis, we found that for growing seasons since 1960, annual harvest dates of the white wine have been getting early as temperature increases (−5.92 days $°C^{-1}$) and more intense precipitation events occur (−1.51 days/(mm/NRD)). Our results indicate a fundamental role of the precipitation intensity in the grape wine phenology that reinforces the impact of the increasing temperature. While the effect of temperature increase can be compensated by that of the total amount of rain, the increase of precipitation intensity could accelerate the possible difficulties to grow some grapes varietal in traditional wine country, expected under warming climate (Hannah et al., 2013). Cook and Wolkovich (2016), using historical data of different wine grape varietal from France and Switzerland found a rate of early harvests with warmer temperature of −6 days $°C^{-1}$ (as average of all the varietals), which is comparable to what observed in our work. A similar result is also observed in Spain for the Chardonnay varietal (−5.3 days $°C^{-1}$) (Ramos et al., 2008), whereas Webb et al. (2012), in Australia, analysing five different grape varietals, reported a greater variability and lower GHD advance. Our results, in terms of the temperature influence on GHD, confirm that in Europe the trigger of the temperature on wine grape phenology is widespread and with similar rate of GHD advance. While the impact of the temperature on early GHD confirms and is comparable with previous studies, the result showing that precipitation intensity does not mitigate the effect of the total amount of precipitation (Cook and Wolkovich, 2016; Fu et al., 2014; Sun et al., 2018), is a novelty. This finding is of some concern since it exacerbates the effects of temperature, even if this needs to be confirmed with further analyses in other areas and for different wine grape varietals. Moreover, even though the role of precipitation intensity is statistically significant and supported by two different models, the availability of other parameters such as soil erosion, evolution of soil properties like pH would help to confirm, strengthen and generalize the impact of the changes of precipitation intensity on GHD.

Changes of irrigation, temperature adaptation strategies, and consumer's preferences could mitigate the effects of temperature and precipitation intensity increase on advancing GHD (Noah et al., 2011; Wolkovich et al., 2018). However, in the future devising mitigation strategies will become more challenging because models suggest that heavy rain events are likely to intensify in several regions around the world (Trenberth, 2011; Hannah et al., 2013). In any case, for wineries that want to use the same cultivation techniques they have had for decades or centuries, with minimal fertilization and irrigation, producing premium wines could become more difficult or even impossible.

5. Conclusion

This study contributes to understand how climate change is influencing crops and agriculture. Our analyses confirm that global warming is affecting premium wines in Central Italy, inducing early GHD at similar rate to what observed in France, Switzerland and Spain. Moreover, we found that the increase of precipitation intensity, observed in the last decades, is the other factor triggering the GHD advance. Even if the impact of precipitation intensity, not yet considered in previous studies of GHD changes, is one-fourth of the temperature one, it could be relevant on the studies of climate change impacts for a couple of reasons: 1) while the total amount of rain is reported to induce a delay of the GHD, the precipitation intensity has the opposite effect; 2) future climate scenarios predict a further increase of heavy precipitations, therefore if confirmed, the advance of GHD could be faster than what can be predicted considering only temperature and the total amount of precipitation, with consequences on quality and quantity of future premium wines. Further studies are desirable to confirm and generalize the finding of this work to other wine grape varietals and other regions.

Acknowledgments

Many thanks to Francesco Paolo Valentini for providing the wine-grape harvest data, for giving access to the documents of the archives of his vinery and family, and for helpful discussion about wine and climate. We thank Mario Cerasoli and Antonio Iovino of the Centro Funzionale of the Abruzzo Region for providing the meteorological time series and for all the details about the meteorological stations, and Manuela Rastelli who helped in revising and improving the English of the manuscript. E.A.'s work was partially supported by DISPUTER research funds (ex-60%).

Author contributions

P.D.C. designed the research, conducted the analysis and model simulations. P.D.C. wrote the original draft. P.D.C., W.H.B. and E.A. wrote the reviewed manuscript. E.A. processed the local meteorological data and conducted the homogenization. All authors discussed the study results and reviewed the manuscript.

Declaration of Competing Interest

The authors declare no competing financial interests and no competing non-financial interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.05.449.

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