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Adaptive capacity of winegrape varieties cultivated in Greece to climate change: current trends and future projections

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ABSTRACT

Aim: This research aimed to: (1) investigate the relationships between harvest dates and berry composition with air temperature during important periods during the growing season, across a range of indigenous and international winegrape varieties grown in wine regions over the majority of Greece; (2) calculate growing degree-days (GDD) from 1st of April until the harvest date of each variety and group the winegrape varieties according to their heat requirements; and (3) predict future harvest dates based upon these heat requirements under different representative emission pathways (*i.e.*, RCP4.5 and RCP8.5) and future time periods (2041-2065 and 2071-2095) using an ensemble projection dataset.

Methods and results: The analysis of heat requirements based on GDD from 1st of April to harvest date identified consistent maturity groups of the varieties studied, especially for indigenous Greek varieties. Trend analysis using the basic linear regression model showed that harvest dates have shifted earlier, during the last few decades, due to warmer conditions (especially during the ripening period) in most cases. In addition, trends in potential alcohol (acid) levels were found to be positively (negatively) correlated with maximum air temperatures in the majority of cases. Analysis of future projections using a global multi-climate model ensemble dataset (10 regional climate models) showed that harvest dates are projected to shift earlier up to 40 days in two future time periods (*i.e.*, 2041-2065 and 2071-2095) depending on the variety and the emission pathway.

Conclusions: Harvest dates of the early ripening varieties were associated more with the variations in maximum air temperatures during March to July, while mid- and late ripening varieties appeared to be affected more by maximum air temperatures during the ripening period. In addition, late ripening, mostly indigenous, varieties were less impacted by temperature increases compared to international varieties.

Significance of the study: The indigenous Greek varieties appear better adapted to the recent and projected future climate of the region, responding less to warming as compared to international varieties in the majority of the study cases.

KEYWORDS

grape, early/late ripening, harvest, temperature, heat requirements

Supplementary data can be downloaded through: https://oeno-one.eu/article/view/3129

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INTRODUCTION

Vineyard productivity is strongly related to climate, therefore atmospheric temperature increases due to climate change have been shown to affect both grape yield and composition and wine organoleptic properties (Schultz, 2000). Additional warming of about 1.0-3.7 °C projected, on average, by the end of the century (IPCC, 2014) would substantially alter the current grapevine geographical distribution, possibly placing areas at low latitudes at danger (Fraga *et al.*, 2016). Especially in regions like Greece (which is located in the warmer part of the Mediterranean basin) vineyards might need to migrate to higher elevations depending on the rate and magnitude of warming in the future (Koufos *et al.*, 2017).

Wine production has a strong economic and social importance in many countries worldwide and thus, the studies investigating the possible future climate threats on viticulture have increased in the past couple of decades (*e.g.*, Teslić *et al.*, 2018). A major part of the research in this area focuses on the effects of climate change on grapevine phenology (growth cycle duration and precocity) reporting significant earlier occurrence of grapevine developmental stages due to warming growing season temperatures (*e.g.*, Webb *et al.*, 2011) thereby placing ripening during a warmer period of the year. The resulting higher temperatures during the maturation phase are very likely to contribute to an increase in sugar levels and a decrease in acid concentrations of the grape composition at harvest (Neethling *et al.*, 2012). Furthermore, higher night-time temperatures have been shown to impair the synthesis and favor the breakdown of secondary metabolites (aroma and color compounds) in berries (Kliewer, 1973; Gaiotti *et al.*, 2018).

The viticultural community has recently focused on investigating the adaptive capacity of the most economically important winegrape varieties to climate change (Wolkovich *et al.*, 2018). To successfully adapt grapevine varieties to the changing thermal conditions, phenology which is mainly driven by temperature has been the key parameter examined (García de Cortázar-Atauri *et al.*, 2017). Therefore, the identification of the specific thermal requirements per variety to reach full berry ripeness could provide a valuable tool for grape growers to plan mitigation strategies to adjust to future climate change (Parker *et al.*, 2013; van Leeuwen *et al.*, 2008).

Greece has played an important role in the development of viticulture and wine production and continues today with a great tradition in winemaking from the ancient times. Traditionally, Greek grape growers cultivated predominantly local grape varieties (over 200). Later, in the second half of the 20th century, many international varieties were introduced to Greece and are now widely cultivated. Two previous studies (Koufos *et al.*, 2014; Koufos *et al.*, 2017) analyzed the characteristics and trends of climate parameters as well as their relationship with viticulture, for the most important winegrape areas and local varieties in Greece. The results showed that: (I) island locations faced proportionally more extreme temperatures and drier conditions compared to mainland and coastal areas, (II) minimum air temperatures increased at a higher rate than maximum temperatures in the majority of winegrape areas, and (III) harvest in the future is projected to occur significantly earlier for most of the areas and varieties.

This research adds to this knowledge by reporting data on an extended number of winegrape varieties (both indigenous and international) and locations across the Greek territory, with the aim to: (1) investigate the relationships of air temperature calculated over different periods with grape harvest dates and chemical composition [*i.e.*, Potential alcohol (%) and acidity (g/L) levels], (2) calculate heat requirements (GDD) from 1st of April to harvest and group the most important winegrape varieties according to their heat requirements, and (3) predict future harvest dates based upon these heat requirements under different representative emission pathways (*i.e.*, RCP4.5 and RCP8.5) in two future time periods (2041-2065 and 2071-2095), using an ensemble projection from 10 regional climate models.

The significance of the present research lies in incorporating 14 wine producing regions covering roughly 90 % of the country's grapevine acreage and production, over a time period of approximately 20 years (from 2000 to 2017, on average) with the aim to predict how climate change may transform Greek grape producing regions and variety distributions in the future. These observations are very important since Greece is one of the warmest winegrape regions in the world (Koufos *et al.,* 2017) and as such could be considered as a useful model for other viticultural regions that may face similar conditions in the near future. Moreover, Greek varieties (indigenous) constitute an important genetic pool for the

adaptation of the wine sector to future climate because of their high suitability to local (semiarid) ecological conditions, therefore establishing their heat requirements would increase the knowledge of and potential utilization by the international viticultural community.

MATERIALS AND METHODS

1. Grape and Harvest Data

Primary data of harvest dates and berry composition (potential alcohol levels and acid concentrations) were assembled from representative wineries and vineyards across the Greek territory (Figure 1). In particular, the harvest date dataset consisted of 29 varieties (16 indigenous and 13 international) that were either cultivated in a specific area, or in various plots within the same area or in different areas, creating a total number of 49 study cases (Table 1). Harvest date as defined by the producers, is the time-point at which, after a number of consecutive measurements by company representatives, no further change in sugar accumulation is observed. Similar definitions of harvest and maturity dates have been used before (*e.g.*, Tomasi *et al.*, 2011). Berry composition data (potential alcohol and acidity of the must) was recorded at harvest after the picking of the grapes. The harvest dates and berry composition dataset details are presented in Tables 1-3. The database described above, was provided from each producer separately based upon maintaining anonymity, is not freely available. The majority of the areas studied are under protected designation of origin (PDO) cultivated with local varieties while the rest are geographical indications (PGI). Overall, the areas studied adequately represent the spatial distribution of wine production in Greece, covering areas with multiple "*terroir"* aspects considering the varieties, the complex topography (*e.g.*, a wide range of elevation, slope, and orientation in the vineyards), geology (*e.g.*, type of soil, inclination, and proximity to water bodies), legislation (*e.g.*, restrictions in irrigation) and cultivation methods.

2. Climate Data

In order to investigate the relationships between air temperature and harvest dates and berry composition, daily observations of maximum (TX) and minimum (TN) air temperature (°C) were obtained from the Hellenic National Meteorological Service (HNMS) which provided sufficient long-term climate records for the regions studied. The 14 weather stations were previously checked for errors and used for climate trend analysis and winegrape region classifications as they appeared to reflect the general structure for climatic conditions of the wine producing areas in Greece (Koufos *et al.*, 2017). The average distance between weather stations and vineyard locations is approximately 20 km [ranged from 50 km (the Kavala region) to less than 10 km (in 6 cases)].



FIGURE 1. Map of Greece showing the locations of the winegrape regions used in this study.

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TABLE 1. Harvest date and air temperature details for the 29 *Vitis Vinifera* winegrape varieties used in this study (16 indigenous and 13 international varieties) for the principal winegrape regions in Greece. Varieties and regions presented in the first two columns. Averages and standard deviation (in parenthesis) for harvest dates are given in column 3. Trend direction (- or +) and slope (*b* coefficient) for harvest dates given in column 4. The relationships between harvest dates and TXMarchJuly [for the early (E) ripening varieties] and TXRP [for mid (M) and late (L) ripening varieties] are given in column 5 with the values representing days per 1 °C. The period of record for harvest dates is given in the last column.

Variety	Region	Average (Standard Deviation)	Harvest Date Trends	Harvest Date/ TX-marchJuly and TXRP Slope	Period of Record
Muscat blanc [E,W,b]	Samos	5 August (5.8)	**-0.35**	**-5.43**	1985-2017
Sylvaner [E,W,b]	Crete	18 August (9.8)	**-1.76**	**-11.97**	2003-2013
Sauvignon blanc [E,W,b]	Drama	16 August (6.0)	**-1.07**	**-5.87**	2004-2017
	Kavala	20 August (4.2)	-0.15	**-3.59**	2001-2017
	Maronia	19 August (3.0)	***-0.41***	**-2.55**	2005-2017
Chardonnay [E,W,b]	Crete	17 August (10.2)	**-2.05**	**-12.26**	2003-2013
	Drama	22 August (7.7)	**-1.15**	**-7.19**	2004-2017
	Kavala	29 August (5.3)	-0.30	**-4.82**	2002-2017
	Tripoli	9 September (7.3)	-0.43	**-4.79**	2001-2017
	Maronia	15 August (3.8)	-0.32	**-2.78**	2005-2017
Malagouzia [E,W,a]	Crete	14 August (9.4)	**-1.88**	**-11.81**	2003-2013
Traminer [E,W,b]	Chalkidiki	19 August (4.2)	**-0.48**	**-3.13**	2001-2017
Liatiko [E,R,a]	Tripoli	15 September (7.4)	-0.29	**-4.58**	2001-2017
Malvasía Aromática [E,W,b]	Crete	26 August (9.5)	-0.92	**-11.09**	2003-2011
Riesling [E,W,b]	Crete	25 August (11.7)	***-1.84***	**-13.66**	2003-2013
Muscat of Alexandria [M,W,b]	Tripoli	20 September (8.7)	***-0.71***	-2.24	2001-2017
Vilana [M,W,a]	Limnos	4 September (9.3)	**-0.56**	**-4.46**	1974-2017
Merlot [M,R,b]	Crete	31 August (8.8)	***-1.02***	-5.70	2003-2016
	Drama	1 September (5.0)	-0.19	**-2.65**	2004-2017
	Kavala	29 August (6.1)	**-0.66**	**-3.70**	2001-2017
	Naousa	27 August (7.5)	-0.21	**-2.81**	1991-2017
	Maronia	26 August (6.3)	-0.40	-2.07	2005-2017
Athiri [M,W,a]	Rodos	23 August (4.8)	**0.36**	**2.36**	1990-2017
Moschofilero [M,W,a]	Tripoli	2 October (6.5)	***-0.55***	**-2.11**	2001-2017
Plyto [M,W,a]	Crete	2 September (5.1)	-0.72	***-4.38***	2006-2016
Sangiovese [M,R,b]	Drama	8 September (12.2)	-1.18	**-4.94**	2004-2017
Vidiano [M,W,a]	Crete	4 September (12.0)	-0.23	-6.61	2008-2016
Assyrtiko [M,W,a]	Santorini	10 August (5.2)	**-0.41**	***-2.08***	1993-2017
	Drama	8 September (8.0)	-0.50	**-4.27**	2004-2017
	Kavala	18 September (7.2)	**-1.14**	**-3.75**	2002-2017
Syrah [M,R,b]	Chalkidiki	25 August (5.5)	-0.21	***-2.11***	2001-2017
	Kavala	10 September (7.8)	**-1.23**	**-4.17**	2002-2017
	Naousa	8 September (10.3)	***-0.48***	**-4.68**	1991-2017
	Nemea	10 September (9.9)	**-1.82**	**-5.28**	2004-2017
Cabernet-Sauvignon [L,R,b]	Crete	4 September (10.6)	-1.11	**-8.94**	2003-2013
	Drama	18 September (6.5)	***-0.79***	**-3.13**	2004-2017
	Kavala	10 September (8.3)	**-1.42**	**-4.41**	2002-2017
Kotsifali [L,R,a]	Crete	15 September (8.3)	0.12	**-8.97**	2003-2013
Agiorgitiko [L,R,a]	Drama	23 September (9.8)	-1.20	**-3.70**	2005-2016
	Kavala	17 September (6.8)	**-1.07**	**-3.54**	2002-2017
	Nemea	17 September (9.5)	**-1.76**	**-4.29**	2004-2017
Limnio [L,R,a]	Maronia	10 September (9.9)	-0.12	**-4.88**	2005-2017
Mandilari [L,R,a]	Crete	17 September (8.5)	***-0.98***	**-8.01**	2003-2016
Nebbiolo [L,R,b]	Drama	20 September (12.7)	**-1.69**	**-4.44**	2004-2017
Roditis [L,R,a]	Nemea	19 September (9.4)	-0.61	**-3.55**	1998-2016
	Aigialia	1 October (8.1)	-0.45	**-3.56**	2005-2017
Daphni [L,W,a]	Crete	23 September (6.7)	-0.02	**-5.70**	2006-2015
Mavrodaphni [L,R,a]	Pyrgos	16 September (9.7)	**-0.75**	**-4.48**	1989-2017
Xinomavro [L,R,a]	Naousa	23 September (6.3)	***-0.17***	**-2.75**	1980-2017
Summary	Early	24 August (7.1)	-0.88	-6.73	
	Mid	3 September (7.8)	-0.64	-3.81	
	Late	19 September (8.6)	-0.78	-4.67	
	Red	11 September (8.6)	-0.83	-4.78	
	White	29 August (7.1)	-0.70	-5.21	
	International	30 August	-0.90	-5.53	
	Indigenous	10 September	-0.58	-4.38	
	Overall	4 September (7.8)	-0.76	-5.01	

Bold letters indicate statistically significant trends (p-value < 0.05), while italicized bold letters indicate lower statistical significance (p-value < 0.10). Each variety has superscript letters indicating indigenous (a) and international varieties (b); early (E), mid (M) and late (L) season varieties; and red (R), white (W) varieties.

In the cases (5 of the 10) with moderate elevation differences between weather stations and vineyard locations, an average lapse rate (0.6 °C per 100 m) adjustment to recorded temperatures was applied to better represent the temperatures in the vineyard areas (Table S1).

To estimate heat requirements (GDD), 29 winegrape varieties with sufficient data, currently grown in 12 out of 14 regions, were selected. For these locations, the HNMS provided sufficient daily data for 10 out of 12 regions. In addition, a commercial website (*i.e.*, www.meteo.gr) that distributes high quality daily observations was used for shorter climate series in the case of Nemea due to the proximity to the vineyards (3 km vs. 18 km) while a weather station network located inside the vineyard area was used for the Drama region. Initially these two data sources (HNMS and Meteo) were combined to account for gaps in the Drama and Nemea timeseries, which works reasonably well with temperatures, however to avoid over or under-estimations in GDD summations we used data from a single station for these sites (Matese *et al.,* 2014; Fourment *et al.,* 2017).

To examine future climates, the DEAR-Clima database was used (http://meteo3.geo.auth.gr:3838/). DEAR-Clima is a reliable, user friendly open access online data source with future climate data from high resolution (0.11° x 0.11°) regional climate models from the Coordinated Regional Downscaling Experiment (CORDEX) research program. In this study, future harvest projection analysis was performed using daily simulations of TX and TN from 10 regional climate models (Table S2). The representative emission pathways 4.5 (RCP4.5) and 8.5 (RCP8.5) were employed in order to project harvest dates in two different time windows [future period 1 (FP1): 2041-2065 and future period 2 (FP2): 2071-2095]. The TX and TN scenarios for FP1 and FP2 were then constructed by adjusting the historical time series with the mean monthly changes (positive or negative) estimated between the control (CP) and FP1 and FP2 time series during the period 1981–2005 (Koufos et al., 2017). Finally, an ensemble projection for each region of interest was then computed as the daily average from the 10 regional climate models.

3. Period Definitions and Variable Selection

In order to investigate the relationships between harvest time, grape potential alcohol and acidity with air temperature, a preliminary analysis examining relationships between maximum (TX) and minimum (TN) temperatures over numerous time periods (*e.g.*, March-September, April-September, March-July, June-July, ripening period, etc.) found that March-July, June-July, and the ripening period were the most important (data not shown). As such TX and TN were used to compute the following variables:

- For harvest time dependence on temperature, TX and TN were calculated for March-July (*i.e.*, TXMarchJuly, TNMarchJuly) and also for the ripening period (RP) (*i.e.*, TXRP, TNRP). It is considered that ripening period (RP) starts at véraison and lasts approximately 45 days in the Northern Hemisphere (Conde *et al.*, 2007).
- For the sugar content of grapes at harvest (potential alcohol), TX and TN were calculated for the RP (TXRP, TNRP) since sugar accumulation in berries takes places entirely during this phase (Davies and Robinson, 1996).
- For the acid concentration of grapes at harvest, TX and TN were computed for June to July (*i.e.*, TXJuneJuly, TNJuneJuly), corresponding on average to the first period of berry development where tartaric acid synthesis takes place (Iland and Coombe, 1988).

A preliminary analysis examining relationships between maximum (TX) and minimum (TN) with harvest, grape potential alcohol, and acidity found that maximum temperatures (TX) during TXMarchJuly, TXJuneJuly, and TXRP were most important (data not shown). Given this result, all further temperature analyses were done only with maximum temperatures during these periods.

4. Variety Heat Requirements

For assessing each varieties' heat requirements, growing degree-days (GDD, Winkler *et al.,* 1974) were calculated using the standard formula:

$$GDD = \sum \left[\frac{(TX + TN)}{2}\right] - \text{Tbase}, \quad \left\{ \begin{matrix} Tbase = 10℃ \\ if \frac{(\text{TX} + \text{TN})}{2} - \text{Tbase} \leq 0,0 \end{matrix} \right\}$$

Each varieties' heat requirements are then calculated as the growing degree-days accumulated over the period 1st of April to the date that harvest was observed for each variety. The date of harvest was determined to be the day when, after a number of consecutive measurements, no further change in sugar accumulation occurred (Tomasi *et al.*, 2011).

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Although the onset of the developmental cycle of the grapevine (*i.e.*, budbreak) may occur slightly earlier or later (*e.g.*, in mid-March or mid-April) depending on the variety, pruning date and region, a fixed starting point (*i.e.*, 1st of April) for all varieties was selected. In order to calculate the GDD units of the studied varieties in Greece we used harvest dates records for the last 14 consecutive years for the majority of cases (except for the winegrape regions of Crete, with 11 years on average and the regions of Drama and Nemea, with 9 years).

5. Statistical Analysis

Initially, to evaluate the consistency of varietal classification according to heat units, a K-mean clustering analysis was performed on the GDD series for each variety (Hartigan and Wong, 1979; Fraga *et al.,* 2015). Three clusters were chosen to group the varieties studied into typical maturity grapevine classes (*i.e.*, early, mid-season, and late ripening varieties).

A generalized linear model procedure was performed to investigate the relative influence of maximum temperature (TX) averaged over different periods (TXMarchJuly and TXRP) on harvest dates considering the three maturity groups (Tomasi *et al.*, 2011). The comparison was based on the AIC criterion (results not shown). The temporal evolution of climatic and viticultural parameters (*i.e.*, harvest dates and berry composition) as well as the relationships between each parameter and the selected temperature variable and period (*i.e.*, TXMarchJuly, TXJuneJuly, and TXRP) were explored using the basic linear regression model ($Y = a + bX$). Statistical significance was evaluated at pvalue < 0.05 and < 0.10.

In order to investigate the potential different harvest date responses to maximum air temperature variation among the varieties, the Z-Score was calculated for each variety by subtracting the mean harvest date shift considering all varieties (*i.e.*, -5.26; negative value denotes earlier appearance) and time series from harvest date shift of each variety and then dividing the difference by the standard deviation of the overall mean (*i.e.*, 3.20) using the following formula:

$$z = \frac{x - \bar{x}}{S}$$

where $\bar{x}$ is the sample mean and S the standard deviation of the sample.

Mean harvest date shift (*i.e.*, -5.26) was calculated as the summation of harvest date response (*i.e.*, slope *b* from the linear regression models) to maximum air temperature of each variety over the period of records divided by the total number of varieties studied (*i.e.*, 29). The harvest date shift of each variety is simply the slope of the linear regression model between harvest dates and maximum air temperature. As an example, the ZScore for Xinomavro (mean harvest shift -2.7) is calculated as follows:

$$-2.7 - (-5.26) / 3.20 = 0.80$$

Therefore, the ZScore of 0.80 for the Xinomavro variety indicates that the harvest response for the specific variety is above the mean harvest response with all varieties considered by 0.80 standard deviations.

Future harvest dates were estimated by accumulating GDD from 1st of April until the specific optimum heat requirement for each variety is reached. All computations, statistical analysis, and figures were performed and created using the R statistical software and R packages (R Core Team, 2014).

RESULTS

1. Harvest Dates and Grape Composition

The analysis showed an average harvest date in Greece by 4 September (± 8 days) across the regions and varieties (Table 1). White varieties are harvested on average by 29 August (ranging from 5 August to 23 September, ± 7 days) while red varieties are harvested on average 11 September (ranging from 6 September to 2 October, ± 9 days). The earliest variety to harvest is on average Muscat blanc in Samos (5 August) while the latest variety to harvest is on average Moschofilero in Tripoli (2 October). By groups, the early maturing varieties average 24 August (± 7 days) while mid and late maturing varieties average 3 September (± 8 days) and 19 September (± 9 days), respectively.

For those regions and varieties with potential alcohol data at harvest, the average across all varieties and regions was 13.4 % (± 0.5 %) with Moschofilero in Tripoli having the lowest values (11.4 %) and Merlot in Drama having the highest values (15.2 %) (Table 2). White varieties averaged slightly lower potential alcohol at harvest than do red varieties (12.7 % vs. 13.9 %). Similarly, early maturing varieties (12.8 %) averaged lower potential alcohol than mid or late maturing varieties (13.4 % and 13.7 %, respectively).

For acid concentrations at harvest, the average was 4.6 g/L varying ± 0.4 g/L across all regions and varieties (Table 3). The lowest acid concentration at harvest was observed with Syrah and Chardonnay in the Kavala region (3.5 g/L) while the highest acid concentration was observed with Chardonnay in the Maronia region (7.3 g/L). White varieties tend to have higher average acidity (5.0 g/L) compared to red varieties (4.4 g/L). Early maturing varieties averaged 5.0 g/L at harvest, while mid maturing varieties had lower average acidity at harvest (3.9 g/L) compared to later maturing varieties (4.9 g/L).

TABLE 2. Potential alcohol and air temperature details for the 12 *Vitis vinifera* winegrape varieties used in this study (7 indigenous and 5 international varieties) for the principal winegrape regions in Greece. Varieties and regions presented in the first two columns. Averages and standard deviation (in parenthesis) for potential alcohol are given in column 3. Trend direction (- or +) and slope (*b* coefficient) for potential alcohol given in column 4. The relationships between potential alcohol and TXRP are given in column 5 with the values representing % per 1 °C. The period of record for potential alcohol is given in the last column.

Variety	Region	Average (Standard Deviation)	Potential Alcohol Trends (%)	Potential Alcohol/ TXRP Slope	Period of Record
Sauvignon blanc [E,W,b]	Kavala	13.3 (0.5)	**0.06**	**0.32**	2002-2017
Chardonnay [E,W,b]	Kavala	13.5 (0.2)	0.02	**0.11**	2002-2017
	Maronia	12.1 (0.7)	0.05	0.26	2005-2017
Malagouzia [E,W,a]	Chalkidiki	12.5 (1.1)	**0.13**	0.14	2001-2017
Merlot [M,R,b]	Drama	15.2 (0.6)	0.07	**0.32**	2005-2016
	Kavala	14.4 (0.4)	**0.05**	**0.27**	2002-2017
Moschofilero [M,W,a]	Tripoli	11.4 (0.4)	**0.05**	**0.16**	2003-2017
Vidiano [M,W,a]	Crete	12.9 (0.6)	0.05	0.10	2008-2016
Assyrtiko [M,W,a]	Kavala	13.3 (0.4)	0.02	0.09	2002-2017
	Chalkidiki	12.9 (0.8)	**0.07**	**0.35**	2001-2017
Syrah [M,R,b]	Kavala	13.0 (0.6)	**0.07**	**0.26**	2002-2017
	Nemea	14.0 (0.7)	**0.09**	***0.23***	2004-2017
Cabernet-Sauvignon [L,R,b]	Drama	14.7 (0.4)	0.02	**0.14**	2005-2016
	Kavala	14.2 (0.5)	**0.07**	**0.23**	2002-2017
Agiorgitiko [L,R,a]	Drama	14.4 (0.7)	0.08	***0.17***	2005-2016
	Kavala	13.7 (0.5)	**0.06**	**0.21**	2002-2017
	Nemea	13.6 (0.5)	**0.09**	**0.20**	2004-2017
Mavrodaphni [L,R,a]	Pyrgos	12.4 (0.4)	**0.03**	**0.09**	1989-2017
Xinomavro [L,R,a]	Naousa	13.1 (0.4)	**0.03**	0.04	1993-2017
Summary	Early	12.8 (0.6)	0.07	0.21	
	Mid	13.4 (0.5)	0.06	0.22	
	Late	13.7 (0.5)	0.05	0.15	
	Red	13.9 (0.5)	0.06	0.20	
	White	12.7 (0.6)	0.06	0.19	
	International	13.8 (0.5)	0.06	0.24	
	Indigenous	13.2 (0.6)	0.06	0.15	
	Overall	13.4 (0.5)	0.06	0.19	

Bold letters indicate statistically significant trends (p-value < 0.05), while italicized bold letters indicate lower statistical significance (p-value < 0.10). Each variety has superscript letters indicating indigenous (a) and international varieties (b); early (E), mid (M) and late (L) season varieties; and red (R), white (W) varieties.

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TABLE 3. Acidity and air temperature details for the seven Vitis vinifera winegrape varieties used in this study (2 indigenous and 5 international varieties) for the principal winegrape regions in Greece. Varieties and regions presented in the first two columns. Averages and standard deviation (in parenthesis) for acidity levels are given in column 3. Trend direction (- or +) and slope (*b* coefficient) for acidity levels given in column 4. The relationships between acidity levels and TXJuneJuly are given in column 5 with the values representing g/L per 1 °C. The period of record for acidity levels is given in the last column.

Variety	Region	Average (Standard Deviation)	Acid Trends (g/L)	Acid/TXJune-July Slope	Period of Record
Sauvignon blanc [E,W,b]	Kavala	4.2 (0.3)	-0.02	-0.09	2002-2017
Chardonnay [E,W,b]	Kavala	3.5 (0.3)	-0.01	-0.07	2002-2017
	Maronia	7.3 (0.9)	-0.10	-0.31	2005-2017
Merlot [M,R,b]	Drama	4.4 (0.7)	***-0.09***	-0.09	2005-2016
	Kavala	3.8 (0.3)	**-0.04**	***-0.16***	2002-2017
Syrah [M,R,b]	Kavala	3.5 (0.3)	-0.01	**-0.21**	2002-2017
Cabernet-Sauvignon [L,R,b]	Kavala	3.9 (0.3)	-0.02	-0.05	2002-2017
Agiorgitiko [L,R,a]	Kavala	3.7 (0.3)	**-0.04**	**-0.23**	2002-2017
Xinomavro [L,R,a]	Naousa	7.0 (0.4)	***-0.03***	-0.11	1993-2017
Summary	Early	5.0 (0.5)	-0.04	-0.16	
	Mid	3.9 (0.4)	-0.05	-0.15	
	Late	4.9 (0.3)	-0.03	-0.13	
	Red	4.4 (0.4)	-0.04	-0.14	
	White	5.0 (0.5)	-0.04	-0.16	
	International	4.4 (0.4)	-0.04	-0.14	
	Indigenous	5.4 (0.3)	-0.04	-0.17	
	Overall	4.6 (0.4)	-0.04	-0.15	

Bold letters indicate statistically significant trends (p-value < 0.05), while italicized bold letters indicate lower statistical significance (p-value < 0.10). Each variety has superscript letters indicating indigenous (a) and international varieties (b); early (E), mid (M) and late (L) season varieties; and red (R), white (W) varieties.

2. Variety Heat Requirements and Clustering

The 29 varieties averaged 1750 GDD from the 1st of April until the time-point at which, after a number of consecutive measurements, no further change in sugar accumulation occurred and the fruit was harvested (Tomasi *et al.*, 2011). There was a range in 644 GDD for the lowest required to harvest for Muscat blanc (1425) to the highest required to harvest for Xinomavro (2069) (Figure 2, Table S3). Vintage to vintage variations in GDD to reach harvest average 96 units over all varieties and regions, ranging from a low of 53 units for Malagouzia to a high of 153 units for Assyrtiko (not shown).

A K-means clustering analysis was performed on the GDD units required to reach maturity (harvest) for the 29 grapevine varieties. Figure 2 depicts three variety groups according to the GDD requirements to reach harvest. Cluster 1 consists of 9 winegrape varieties (2 indigenous and 7 international) with the lowest GDD units required for harvest (*i.e.*, Muscat blanc, Sylvaner, Sauvignon blanc, Chardonnay, Malagouzia, Traminer, Liatiko, Malvasía Aromática and Riesling). These varieties are classified as early ripening varieties and ranged from 1425 (Muscat blanc) to 1617 (Riesling) GDD units. The second cluster groups 10 mid-season varieties (6 indigenous and 4 international) varying from 1680 (Muscat of Alexandria) to 1801 (Syrah) GDD units to achieve full maturity. Cluster 3 comprises 10 winegrape varieties (8 indigenous and 2 international). This cluster corresponds to late ripening varieties requiring

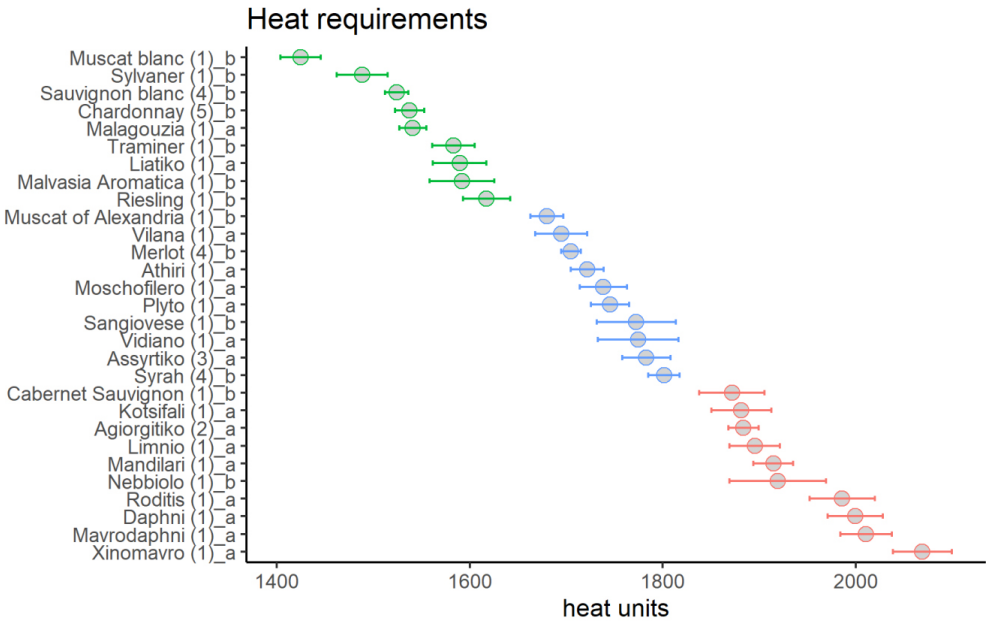


FIGURE 2. Heat requirements for the 29 winegrape varieties (16 indigenous and 13 international) cultivated in Greece.

Heat units are estimated as mean growing degree-days (GDD) from April 1st to the harvest date. Y-axis shows the variety along with the number of vineyard sites used in each case (numbers in parenthesis). Letters a, b indicates indigenous and international winegrape varieties, respectively. X-axis shows the mean GDD units (see Materials and Methods). Horizontal bars represent the lowest and highest values in each case. Varieties are grouped according to the K-means cluster analysis [Cluster 1: early ripening varieties (green colour), Cluster 2: mid-ripening varieties (blue colour) and Cluster 3: late ripening varieties (red colour)].

from 1872 units for CabernetSauvignon to 2069 units for Xinomavro in order to achieve full maturity and are harvested in late September (on average). Comparing GDD units between the 3 clusters, cluster 3 exhibited a wider range of 197 GDD units, while cluster 2 and cluster 1 showed ranges of 121 and 192 GDD units, respectively.

3. Trends in Grapevine Parameters and Relationships with Climate

Overall, while the harvest in Greece was observed to average 4 September, it varied from 5 August (*i.e.*, Muscat blanc in Samos) to 2 October (Moschofilero in Tripoli) (Table 1). Although the vineyards greatly varied in their latitude, elevation, and topography, the international varieties are skewed towards earlier ripening as compared to indigenous Greek varieties (Figure 3). The average harvest date for the international varieties is 30 August compared to 10 September for the Greek varieties (Figure 3).

The overall trend analysis revealed earlier harvest occurrence (negative trends) in 47 out of 49 cases with 18 statistically significant at $\alpha = 0.05$ and 9 at $\alpha = 0.10$ (Table 1). Two cases showed a slight delay in harvest timing, with only the variety Athiri on Rodos being statistically significant. The harvest dates for the early ripening varieties (16 cases) advanced, on average, by -0.88 days per year while harvest dates for the mid-season (19 cases) and late ripening (14 cases) varieties occurred earlier by -0.64 and -0.78 days per year, respectively (Table 1). Additionally, the harvest date evolutions of the international varieties (17 statistically significant cases) showed a stronger earlier occurrence (-1.17 days per year, on average) than the respective indigenous varieties (11 statistically significant cases, -0.72 days per year, on average). Averaged across all varieties and periods, harvest commenced significantly earlier by -0.76 days per year (Table 1).

Harvest date linear regression analysis revealed statistically significant negative relationships with TX during ripening in 44 out of 49 cases (Table 1). An additional 4 cases exhibited negative but non-significant relationships over time, while only one statistically significant case found delayed harvest under warmer ripening conditions (*i.e.*, Athiri on Rodos). Averaged over all varieties and regions, harvest dates exhibited a five-day earlier occurrence per 1 °C (Table 1) and averaged 11 days earlier over the varying time periods of the data. White varieties showed slightly greater sensitivity to warmer conditions compared to red varieties (-5.21 vs. -4.78 days per 1 °C).

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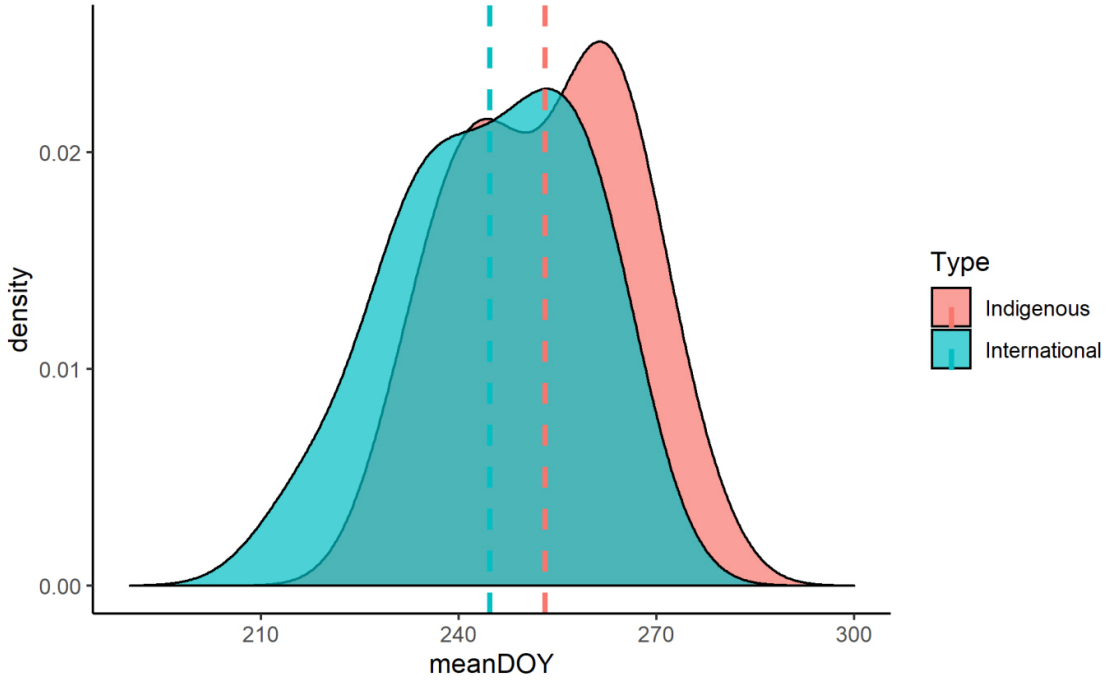


FIGURE 3. Variation in harvest dates across the 29 winegrape varieties examined (16 indigenous and 13 international) and currently cultivated in Greece.
Expressed as DOY (day of year). Vertical dashed blue (red) lines indicate the mean harvest date for the international (indigenous) varieties.

By variety grouping, early varieties were most sensitive with nearly seven days per 1 °C while late varieties responded slightly more than mid ripening varieties (-4.67 vs. -3.81 days per 1 °C). In addition, international varieties responded more to warmer ripening periods (-5.53 days per 1 °C) compared to indigenous varieties (-4.38 days per 1 °C).

Over all varieties and regions with potential alcohol data, the trend average was 0.06 % per year with red and white varieties having similar trends (0.06 % per year) and early and mid-maturing varieties exhibiting higher trends than later maturing varieties (Table 2). During the last couple of decades, potential alcohol at harvest has risen approximately 0.40 % over these varieties and locations. Potential alcohol levels exhibited significant positive relationships with TX during the ripening period in 14 out of 19 cases, while an additional five cases exhibited positive but non-significant associations with TXRP (Table 2). The average slope across all regions and varieties was 0.19 % per 1 °C warmer ripening periods, with little difference between white and red varieties, but with late-ripening varieties exhibiting a lower response than early- or mid-ripening varieties (Table 2). International varieties responded slightly higher than indigenous varieties with 0.24 % vs. 0.17 % per 1 °C warmer ripening periods.

Acid concentrations across all locations and varieties trended lower over the time periods with -0.04 g/L per year on average, with four cases statistically significant (Table 3). No differences in the trends were found for white vs. red varieties, however mid-maturing varieties exhibited a moderately higher trend (-0.05 g/L) than either early (-0.04 g/L) or late (-0.03 g/L) varieties. During the study period acid concentrations at harvest declined on average -0.46 g/L. Acid concentrations presented significant negative relationships with TXJuneJuly in 3 out of 9 cases with 6 more cases exhibiting negative but non-significant associations with maximum air temperatures during the summer (Table 3). The average slope between acid concentrations and TXJuneJuly was -0.15 g/L per 1 °C warmer mid-summer temperatures. Both white varieties and early varieties showed higher trends to lower acid concentrations compared to red or mid to late ripening varieties. However, there was no difference in acid concentrations between international and indigenous varieties.

Regarding maximum air temperature trends during the March-July (for the early ripening varieties) and RP (for the mid and late ripening varieties), the analysis revealed warmer conditions

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TABLE 4. Air temperature details for the 29 Vitis vinifera winegrape varieties used in this study (16 indigenous and 13 international varieties) for the principal winegrape regions in Greece. Varieties and regions presented in the first two columns. Trend direction (- or +) and slope (b coefficient) for TXMarchJuly [for the early (E) ripening varieties] and TXRP [for mid (M) and late (L) ripening varieties] are given in column 3. The period of record for maximum air temperature is given in the last column.

Variety	Region	TXMarchJuly and TXRP trends (°C)	Period of Record
Muscat blanc [E,W,b]	Samos	***0.02***	1985-2017
Sylvaner [E,W,b]	Crete	***0.12***	2003-2013
Sauvignon blanc [E,W,b]	Drama	0.03	2004-2017
	Kavala	***0.06***	2001-2017
	Maronia	0.07	2005-2017
Chardonnay [E,W,b]	Crete	***0.12***	2003-2013
	Drama	0.03	2004-2017
	Kavala	**0.08**	2002-2017
	Tripoli	0.04	2001-2017
	Maronia	0.07	2005-2017
Malagouzia [E,W,a]	Crete	***0.12***	2003-2013
Traminer [E,W,b]	Chalkidiki	0.07	2001-2017
Liatiko [E,R,a]	Tripoli	0.04	2001-2017
Malvasía Aromática [E,W,b]	Crete	0.10	2003-2011
Riesling [E,W,b]	Crete	***0.12***	2003-2013
Muscat of Alexandria [M,W,b]	Tripoli	0.04	2001-2017
Vilana [M,W,a]	Limnos	**0.11**	1974-2017
Merlot [M,R,b]	Crete	0.03	2003-2016
	Drama	**0.14**	2004-2017
	Kavala	**0.12**	2001-2017
	Naousa	**0.09**	1991-2017
	Maronia	0.08	2005-2017
Athiri [M,W,a]	Rodos	**0.06**	1990-2017
Moschofilero [M,W,a]	Tripoli	***0.19***	2001-2017
Plyto [M,W,a]	Crete	-0.01	2006-2016
Sangiovese [M,R,b]	Drama	**0.27**	2004-2017
Vidiano [M,W,a]	Crete	0.06	2008-2016
Assyrtiko [M,W,a]	Santorini	**0.09**	1993-2017
	Drama	***0.19***	2004-2017
	Kavala	**0.30**	2002-2017
Syrah [M,R,b]	Chalkidiki	0.09	2001-2017
	Kavala	**0.28**	2002-2017
	Naousa	**0.11**	1991-2017
	Nemea	**0.21**	2004-2017
Cabernet-Sauvignon [L,R,b]	Crete	0.03	2003-2013
	Drama	**0.26**	2004-2017
	Kavala	**0.30**	2002-2017
Kotsifali [L,R,a]	Crete	0.01	2003-2013
Agiorgitiko [L,R,a]	Drama	**0.41**	2005-2016
	Kavala	**0.29**	2002-2017
	Nemea	**0.26**	2004-2017
Limnio [L,R,a]	Maronia	0.12	2005-2017
Mandilari [L,R,a]	Crete	0.08	2003-2016
Nebbiolo [L,R,b]	Drama	**0.42**	2004-2017
Roditis [L,R,a]	Nemea	**0.19**	1998-2016
	Aigialia	0.15	2005-2017
Daphni [L,W,a]	Crete	0.10	2006-2015
Mavrodaphni [L,R,a]	Pyrgos	**0.14**	1989-2017
Xinomavro [L,R,a]	Naousa	**0.07**	1980-2017

Bold letters indicate statistically significant trends (p-value < 0.05), while italicized bold letters indicate lower statistical significance (p-value < 0.10). Each variety has superscript letters indicating indigenous (a) and international varieties (b); early (E), mid (M) and late (L) season varieties; and red (R), white (W) varieties.

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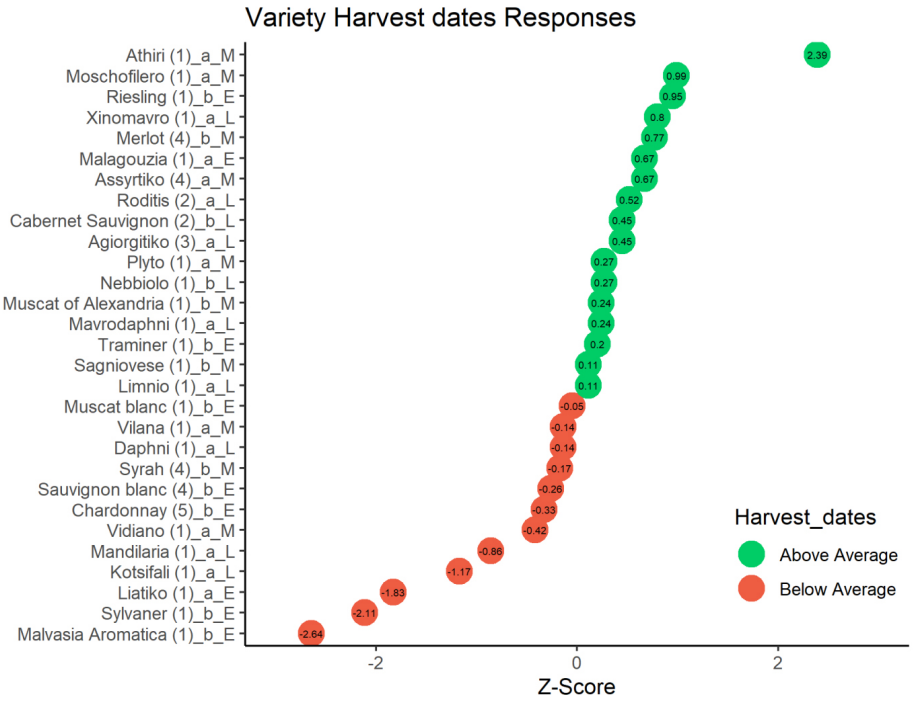


FIGURE 4. Harvest date responses for the 29 winegrape varieties studied (16 indigenous and 13 international) in Greece.

Y-axis shows the variety along with the number of vineyard sites used in each case (numbers in parenthesis). Letters a, b indicates indigenous and international winegrape varieties, while E, M and L represent early, mid-season and late ripening varieties, respectively. X-axis shows the Z-Score (see Materials and Methods). The varieties with Z-Score above (below) zero are marked green (red) respectively.

in 48 out of 49 cases with only one exception (Table 4). Of the statistically significant warming trends, positive ones were observed in 29 out of 49 cases. With regard to the average trends between the March-July and ripening period, the ripening period warming rate was +0.09 °C higher than the rate during the March-July period (0.16 vs. 0.07 °C, respectively, Table 4). It also important to note that during the period of records for these locations TN and average air temperature were also correlated with viticultural parameters but with lower magnitude (not shown).

Figure 4 shows the response of harvest date of each variety as a function of the average harvest date shift (ZScore), with all varieties considered. Harvest dates for the mid-season and late ripening varieties (7 out of 10 cases for each) generally responded at a slower rate (positive index) to changes in temperature compared to early varieties (with the exception of Traminer, Riesling and Malagouzia). In addition, the majority of the varieties in the winegrape region of Crete (10 out of 12 cases) (both indigenous and international) showed the strongest responses to temperature (negative index).

4. Future Climate Change Impacts on Harvest Dates

In order to project future harvest responses, the GDD heat units were calculated for a set of 29 (16 indigenous and 13 international) winegrape varieties for an ensemble future climate with two emission pathways (*i.e.*, RCP4.5 and RCP8.5), derived from 10 regional climate models. The results are presented in Figure 5 and Figure 6. For the FP1 period (*i.e.*, 2041-2065) and under the lower emission pathway (*i.e.*, RCP4.5), the harvest dates of the late ripening varieties, which currently occur in mid-September, are projected to occur approximately 20 days earlier compared to the CP, while under FP2 the harvest is further advanced by 6 days. The higher emission pathway (*i.e.*, RCP8.5) led to even more noticeable shifts. Overall, harvest for the late ripening varieties is projected to become earlier by over a month (*i.e.*, almost 40 days) by the end of the century (FP2). The indigenous varieties of Mavrodaphni, Agiorgitiko, Roditis, Xinomavro and Limnio, exhibited the lower responses (19 and 35 days earlier on average, according to RCP4.5 and RCP8.5, respectively, Figures 4 and 5) while three varieties from Crete (*i.e.*, Mandilaria, Kotsifali

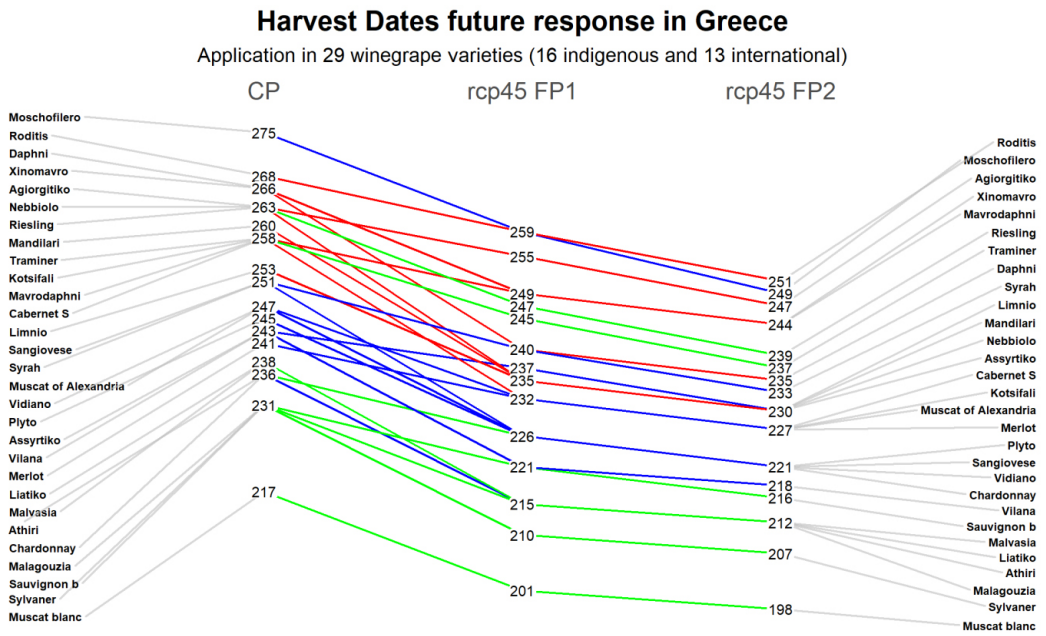


FIGURE 5. Current and projected harvest dates for the 29 winegrape varieties studied (16 indigenous and 13 international) in Greece.

The left vertical axis (*i.e.*, Y-axis) shows the current time of maturity (CP) of the selected varieties while the right vertical axis shows the future projection of the date of maturity. The horizontal axis (*i.e.*, X-axis) shows the mean DOY evolution in days according to the RCP4.5 emission pathway and time windows (FP1: 2041-2065) used in this study. Early, mid-season and late ripening varieties are presented with green, blue, and red lines, respectively. Numbers represents the time of maturity according to Julian date [(mean DOY) *e.g.*, 275: 02 October, etc.)] (created using the R package CGPfunctions, Chuck Powell, 2019).

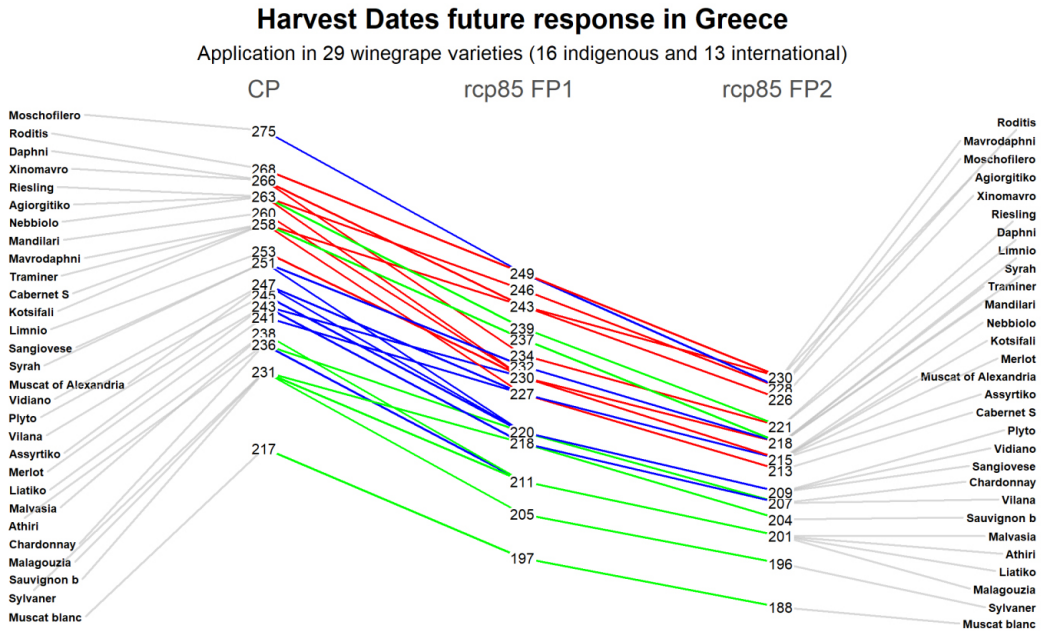


FIGURE 6. Current and projected harvest dates for the 29 winegrape varieties studied (16 indigenous and 13 international) in Greece.

The left vertical axis (*i.e.*, Y-axis) shows the current time of maturity (CP) of the selected varieties while the right vertical axis shows the future projection of the date of maturity. The horizontal axis (*i.e.*, X-axis) shows the mean DOY evolution in days according to the RCP8.5 emission pathway and time windows (FP1: 2071-2095) used in this study. Early, mid-season and late ripening varieties are presented with green, blue, and red lines, respectively. Numbers represents the time of maturity according to Julian date [(mean DOY) *e.g.*, 275: 02 October, etc)] (created using the R package CGPfunctions, Chuck Powell, 2019).

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and Daphni) along with the international varieties of CabernetSauvignon and Nebbiolo showed the more pronounced shifts. The mid-season varieties (10 cases), harvested today in early-September, are projected to significantly advance by 17 days, on average, over the FP1 and under the RCP4.5 pathway. In the FP2, the harvest is projected to occur 22 days earlier. According to RCP8.5, two mid-season varieties (*i.e.*, Moschofilero and Sangiovese) are projected to be over 40 days earlier during FP2. Finally, the harvest dates of the early ripening varieties (9 cases), which are currently occurring in the late August (on average), is projected to occur approximately two weeks earlier in FP1 and under the RCP4.5 pathway. The results were more pronounced when the analysis was based on the higher emission pathway and FP2 (34 days earlier) placing harvest in mid to late July.

DISCUSSION

This research adds to the developing knowledge of the relationships between climate (historical and future) and regional wine production in Greece. Greece is a predominately warm to hot climate region for wine production, exhibiting a diversity of landscapes across islands, coastal zones, and mainland elevated areas providing suitable conditions for a wide range of varieties and wine styles (Anderson *et al.*, 2014). Koufos *et al.* (2014) identified that significant trends in climate parameters and viticulture–climate relationships were more evident for island than mainland locations. Moreover, areas with late ripening varieties were less sensitive to changes in climate. Comparing recent (1981-2010) and future conditions (2021–2050 and 2061–2090) over key mainland, coastal and island viticultural areas of Greece, Koufos *et al.* (2017) found that regional climate models suggest significant shifts towards warmer and drier conditions across all regions in Greece in the future.

This study found earlier harvests as well as increased potential alcohol levels and lowered acidity for both indigenous and international varieties cultivated in Greece. These changes were correlated with changes in temperature across the regions studied. In a similar manner, Neethling *et al.* (2012) found significant increasing (decreasing) trends in sugar levels (acid concentrations) in six white and red winegrape varieties in the *vallée de la Loire* (France) that were also mostly explained (nearly 70 %) by the variability in climatic conditions. Higher potential alcohol levels associated with lower titratable acidity, such as those observed in Greece and other regions around the world, could have detrimental impacts on the compositional ratio within the ripening fruit leading to unbalanced wines and lower quality (van Leeuwen *et al.*, 2004; van Leeuwen and Destrac Irvine, 2017).

In this study, harvest dates of the early ripening varieties were associated more with the variations in maximum air temperatures during March to July, while mid and late ripening varieties appeared to be affected more by maximum air temperatures during the ripening period. In addition, the late ripening, mostly indigenous, varieties were less impacted by temperature increases compared to international varieties. Similarly, in the Veneto region of Italy, Tomasi *et al.* (2011) observed that early ripening varieties appeared to react more strongly than the respective mid-season and late ripening varieties to warmer conditions. In general, late ripening varieties often experience a maturation period that does not allow sugars to accumulate to maximum levels, thus warming would result in an improved sugar/acid ratio at harvest but without, or with a smaller shift in harvest timing. On the contrary, for early ripening varieties that consistently reach high sugar levels, warmer temperatures would necessarily lead to an earlier picking of grapes to avoid excessive potential alcohol levels in the wines. However, Ruml *et al.* (2016) reported for Serbia a significant advance in the beginning of harvest in all varieties, by 0.6 days per year on average due to higher average temperatures, showing moderate variability between varieties. Also, according to van Leeuwen and Darriet (2016) the reported harvest shifts related to increasing temperatures are the result of both the general temperature rise (warmer conditions during the whole vine growth cycle) and the resulting advancement of phenological stages, placing the ripening period during a hotter period of the year. This is mostly true for mid-season to late ripening varieties. For early ripening varieties, since maturation already takes place under warm to hot conditions (mid to late August), it is expected that harvest shifts to earlier dates would not significantly affect the thermal conditions of the final period of berry development. As such, changes in harvest dates are probably less related to an increment of the ripening speed but mostly to a general advancement of the whole cycle of grapevine phenology and likely very important during the véraison stage, marking the onset of berry ripening.

It is important to note that harvest needs to be considered carefully since it is not an actual phenological stage, but an event that is based on human judgement which may also depend on other factors such as wine style preference, flavor preference, seed ripening, available labor to harvest the fruit, room in the winery to accept the fruit, etc. (Mira de Orduña, 2010). However, long-term harvest dates have been used in several studies to reconstruct air temperature during the growing season in the past, providing additional insight to climate change impacts on viticulture (Chuine *et al.*, 2004; Daux *et al.*, 2012). Furthermore, designated maturity levels (*i.e.*, harvest at a predetermined specific sugar [°Brix or total soluble solids] or potential alcohol levels) as opposed to the actual harvest date of many varieties also significantly progressed under warmer temperatures in Australia (Webb *et al.*, 2011).

Climate modeling efforts have reported earlier future harvests in many winegrape regions around the world. Two relevant studies in Australia (*i.e.*, Webb *et al.*, 2007; Hall *et al.*, 2016), using different approaches (a grapevine simulation model and a heat requirement method, respectively) and winegrape varieties (*i.e.*, Chardonnay, Cabernet Sauvignon, and Shiraz) found noticeable shifts in harvest and growing cycle length based on a higher emission pathway. Similar results were identified for the widely cultivated variety Pinot noir in Europe (35 principal winegrape regions) (Fraga *et al.*, 2016). Leolini *et al.* (2019) examining future climate change impacts on Sangiovese in Italy, found similar trends to increasing sugar content and declining acid concentrations, but also stressed the importance of examining increasing seasonality of temperatures on top of average temperature changes in climate change studies. From these and other studies it is likely that continued warming will lead to even earlier harvests, shifting the important processes of sugar accumulation and acid degradation further toward the hottest part of the season (*i.e.*, summer months) likely resulting in unbalanced and altered wine flavors and styles. The latter is evident mostly for the early ripening varieties for which measures will be needed to delay the maturation process in the vineyard [*e.g.*, mid-canopy late leaf removal or shoot trimming to reduce leaf area/fruit weight ratio (Poni *et al.*, 2013; Palliotti *et al.*, 2013; Parker *et al.*, 2014)], or to delay the onset of the growing season [*e.g.*, late winter pruning or pruning after budbreak (Friend and Trought, 2007; Petrie *et al.*, 2017; Gatti *et al.*, 2018)].

However, warmer conditions during the vintage and especially during ripening do not necessarily always mean earlier harvests. Using controlled temperature regimes, Greer and Weedon (2014) found that higher temperatures late in the growing season can limit or even stop sugar accumulation and ultimately delay ripening. They also found that the ripening process of grapevine cultivars was temperature-dependent, with the optimum temperature for ripening varying widely from 25 to 40 °C for Chardonnay, Semillon, and Merlot (low to high, respectively). They also found that excessively high temperatures are detrimental to grape development by inhibiting berry growth, delaying sugar accumulation, impeding fruit coloration, causing fruit to shrivel, and may cause abnormal pigmentation of white fruit. Similarly, Ramos and Martínez de Toda (2020) identified in Rioja that grape composition was impacted by higher temperatures with a decoupling between phenolic maturity, anthocyanins, and sugar development along with lower acidity. In the irrigated areas the problem can be reduced with higher irrigation rates, but in rainfed areas there is no ability to use irrigation as a management strategy. In addition, an early study in South Australia by Sadras and Moran (2012), using different temperature regimes, showed that higher temperatures decouples anthocyanins and sugar in Shiraz and Cabernet franc varieties with no effect on the beginning of harvest. Research in Italy by Gaiotti *et al.* (2018) also suggested that the capacity for anthocyanin biosynthesis is enhanced by cool nights during véraison and that heat stress during ripening resulted in color loss, slowing of sugar accumulation, and potential later harvests with decoupled ripening profiles.

From this research, harvest dates, as determined by no further sugar increase after a number of consecutive measurements, exhibited earlier occurrences over numerous varieties and regions in Greece. Establishing heat accumulation requirements provided insights into how these varieties might respond with future warming. However, it is important to note that the GDD approach has some limitations. The accuracy of the GDD index in describing thermal requirements of a given variety is higher when the variety studied systematically reaches complete ripeness in a given area. Among the varieties of cluster 2, heat requirements for Moschofilero are possibly underestimated because in the Mantinia PDO area, one of the coolest in Greece (Koufos *et al.*, 2017), it is commonly harvested at suboptimal sugar levels. In such cases, data for budbreak, flowering and véraison

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stages could be used or the approach proposed by Parker *et al.* (2020) targeting for specific sugar content. However, since such observations are rarely recorded on a regular basis by Greek producers and if so, they are limited to only few varieties and years. To overcome this problem and to achieve a consistent approach for both current and future responses, 1st of April was selected as a starting point, despite the fact that it does not correspond to a phenological stage, and may be out of synchrony with development in future climate conditions.

The standard GDD formula used in this study also has limitations. For one, there is evidence that the base temperature threshold for accumulation is likely cultivar specific and is possibly as low as 5 °C (García de Cortázar-Atauri *et al.,* 2009). Second, it considers that all temperatures above 10 °C have a similar positive and additive effect on grapevine development (it is well known that temperatures > 35 °C, often occurring in Greece, have mostly a negative impact [Greer and Weedon, 2014]). However, both the upper and lower thresholds have not been fully assessed for Greek varieties, therefore we stayed with the standard formula and will pursue research to define these thresholds in the future. Finally, the GDD formula does not account other climatic factors such as rainfall and sunshine hours. For example, the indigenous variety Xinomavro, cultivated in the areas of Amyndeon (near the city of Florina) and Naoussa with different average growing season temperatures (17.6 °C in Amyndeon vs. 19.4 °C in Naoussa), presented harvest date ranging from mid-September (Naoussa) to early October (Amyndeon). As a result, estimated GDD to reach harvest ranges from 1700 in Amyndeon vs. 2069 in Naoussa, for the production of red dry wines of similar style. A possible explanation would be that the Amyndeon region has more sunshine hours which are highly efficient physiologically, whereas Naoussa is characterized by higher precipitation, especially in September (Koufos *et al.* 2017).

Further warming, especially in maximum temperature extremes, could show an opposite response than what has been observed for some varieties in Greece. For example, two indigenous varieties, the mid-ripening white variety Athiri and the late ripening red variety Kotsifali showed a slight delay in harvest in this research, one being statistically significant (Athiri). More research needs to be done, both in controlled and open field experiments, to examine how this variety and others might behave in terms of harvest timing and fruit composition in the face of a changing climate in Greece.

CONCLUSIONS

This research presents the first estimate of heat requirements for both indigenous and international varieties planted across the main wine producing regions in Greece. Both indigenous and international winegrape varieties have harvested earlier with generally higher potential alcohol and lower acidity. These trends have been tied to warming conditions in many Greek wine regions during important growing periods during the vintage. However, the research also points out that late ripening, mostly indigenous varieties were less impacted by recent and projected temperature increases in Greece compared to international varieties. This highlights recent research results (Wolkovich *et al.*, 2018; Morales-Castilla *et al.*, 2020) indicating that both increasing the diversity of varieties planted and better clonal selection (Martinez-Zapater *et al.*, 2010) are potential adaptive responses to a changing climate. To further address these needs, the International Organization of Vine and Wine (OIV) is currently undertaking research that is looking at the selection and improvement of varieties for adaptation to climate change (Compés and Sotés, 2018).

This research indicates that in the future the Greek wine sector is expected to face additional pressure as grape maturity is expected to shift toward warmer summer conditions, likely negatively affecting berry composition and final wine quality. Although the results of varietal clustering with the use of the GDD formula presented in this research are promising, especially regarding the number of indigenous varieties in the late ripening group, adaptation of viticulture to future conditions based on the thermal requirements of the grape varieties alone will probably not be sufficient. The development of a more complex indicator(s) than the traditionally used agro- or bio-climatic indices, capable of incorporating a variety's level of resilience to both heat and drought conditions, will better enable growers and researchers to efficiently select the best varieties and locations for their vineyards for the next generation of wine producers.

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