HARVEST DATES, CLIMATE, AND VITICULTURAL REGION ZONING IN GREECE

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Abstract
Climate is clearly one of the most important factors in the success of all agricultural systems, influencing whether a crop is suitable to a given region, largely controlling crop production and quality, and ultimately driving economic sustainability. Today many assessments of a region's climate comes from a combination of station and spatial climate data analyses that facilitate the evaluation of the general suitability for viticulture and potential wine styles, allows for comparisons between wine regions, and offers growers a measure of assessing appropriate cultivars and sites. This research combines a spatial climate analysis in Greece with a temporal station and harvest date analysis in important Greek wine regions. The results show predominately warm to hot climate suitability in Greece, comparable to many other regions worldwide. While many viticulture regions have one primary class of suitability, variability of climate within regions can be significant, with some regions containing two to four climate classes, typically based on elevation or distance to the coast, making them suitable for a greater range of cultivars. For the temporal analysis the eight locations studied had marked differences in their general climatic characteristics, mainly between mainland and island areas. While trends varied for the regions, the general response was for greater increases in minimum temperatures compared to maximum temperatures, which resulted in significant trends in growing degree-days in most locations. Harvest dates trended earlier in five out of the eight regions, and were mainly driven by changes in minimum temperatures. Significant trends in climate parameters and viticulture–climate relationships were more evident for island regions when compared to mainland locations. Moreover, areas with late ripening varieties were shown to be less sensitive to climate changes.

Keywords: Greece, climate, viticulture, wine, harvest dates

1 INTRODUCTION

Climate is arguably the most decisive factor in every form of agriculture including viticulture. Knowledge of the spatial and temporal variation in temperature in wine regions provides the basis for evaluating the general suitability for viticulture, allows for comparisons between wine regions, and offers growers a measure of assessing appropriate cultivars and sites (Jones et al. 2010). Furthermore, observed changes in climate have had numerous effects, including shifts in grapevine phenological events such as bud break, flowering, veraison and harvest. The time of these events for a given cultivar is mainly influenced by temperature conditions of the growth period (Mullins et al. 1992) and past observations have shown that harvest dates significantly advanced for many varieties across numerous locations in Europe (Jones et al. 2005b; Tomasi et al. 2011). Greece is one of the oldest wine-producing regions in the world. Today, the area cultivated with winegrapes covers approximately 67 000 ha where about 200 indigenous varieties are cultivated (Lacombe et al. 2011). The total production of wine reached 2 660 050 hL in 2012. Despite the importance of the wine sector in the Greek economy and that much is known about the climate of Greece and its influence on wine production, the use of spatial climate data to conduct regional assessments of the climate have been limited. Furthermore, there have been few studies defining the impacts of climate change on Greek viticulture. Thus, the aim of this study is to (1) identify the spatial climate characteristics in wine regions in Greece and (2) evaluate the impact of climate change on harvest dates in Greece.

2 MATERIALS AND METHODS

In this study a spatial assessment of the climates in wine producing regions in Greece and a temporal assessment of harvest dates and climate stations trends were conducted. To assess the spatial characteristics of viticulture regions in Greece we created boundaries of all of the established Designation of Origin Wines for Appellation of Origin of Superior Quality (AOQS) and Appellation of Origin Controlled (AOC). The boundaries of the viticulture areas in Greece were digitized based on official legislation descriptions using administrative limits with restrictions based on elevation information (a digital terrain model was created from contours and trigonometric points) and on transport infrastructure (used as physical limits). All the GIS processes for the creation of the boundaries were done with ArcGIS (v.10) software using appropriate tools (Clip, Erase, Spatial Join, Buffer, Dissolve, TIN creation, etc.). Overall 35 regions are identified in Greece and defined by administrative regions, but with four regions overlapping and only differing in wine types (red or white) or varieties (Figure 1). For the spatial climate assessment the data in this research uses a global database called 'WorldClim' developed by Hijmans et al. (2005). The WorldClim data was created by gathering data from numerous sources (e.g., GHCN, WMO, FAOCLIM, etc.) and stations were interpolated using a thin-plate smoothing spline algorithm implemented in the ANUSPLIN package for interpolation, using latitude, longitude, and elevation as independent variables. The station data is interpolated to a 30 arc second spatial resolution; which is equivalent to about 0.86 km^2 at the equator and less elsewhere, but is close to 1 km in a mid-latitude area such as Greece. The gridded data set provides monthly maximum temperatures, minimum temperatures, and precipitation for 1950-2000, representing the highest resolution available at the global scale for spatial climate analyses (Hijmans et al. 2005). The average monthly maximum and minimum temperature grids were then used to derive three climate indices for Greece: an average growing season temperature index (GST), standard growing degree-days (GDD) as represented in the Winkler Index (WI), and the Huglin Index (HI). These indices were selected based on their previous use and acceptance in understanding climate characteristics favourable for specific winegrape cultivars and the general wine style that can be produced (Jones et al. 2010). Combining the spatial boundaries of the viticulture regions, elevation data, and climate index grids, we then characterized the area, elevation, and climate of each region with summary statistics. For the climate indices, quantile statistics (minimum, 25%, median, 75% and maximum) representing each climate index grid in each region were calculated to give a spatial representation of the climate measures over the entire region (Jones and Alves, 2012).

For the temporal assessment, harvest dates (18 to 37 years) from eight different varieties (five white (W) and three red (R)) and regions were used (Koufos et al. 2013). The harvest dates series come from four mainland regions, Anchialos (cv. Roditis W), Nemea (cv. Agiorgitiko R), Pyrgos (cv. Mavrodaphni R) and Naoussa (cv. Xinomavro R), and four islands, Limnos (cv. Muscat of Alexandria W), Samos (cv. Muscat blanc W), Santorini (cv. Assyrtiko W) and Rodos (cv. Athiri W) (Figure 1). Climate data used in this analysis were obtained from the Hellenic National Meteorological Service (HNMS) for 46 weather stations (including the eight vineyard regions) for the period 1975-2004. Wine region stations were chosen based on their proximity to the vineyards where harvest information was used (<20 km away on average), while the remainder of the stations were used to develop a comparative spatial climatology for Greece (Koufos et al. 2013). The data consisted of daily observations of mean (Tmean), maximum (Tmax) and minimum (Tmin) air temperature and, in five out of eight locations, daily precipitation (Prec.). Climate data were computed for three periods: (1) calendar year (CY: Jan. 1st- Dec. 31), (2) growing season (GS: April 1st – Oct. 31) and (3) ripening period (RP: depending on the variety); then secondary variables commonly used in viticulture studies (Jones and Davis 2000) were calculated: (1) Growing degree days, base 10°C (GDD), (2) diurnal temperature range (DTR) and (3) the number of days with extreme cold (Tmin<0°C) or heat (Tmax>35°C). Finally, harvest anomaly (ΔH) computed as the average difference between the annual harvest date for each year and the long-term mean harvest date. Correlation and regression analyses were used to assess the relationships and trends.

3 RESULTS AND DISCUSSION

The Greek wine regions range in size from less than 50 km^2 in Messenikola and Mosxato Kefallinias to the largest in Xandakas Candia (1202 km^2) and Patra (1292 km^2) (Table 1). Due to island locations, many regions have low median elevations (< 100 m) while others in the interior and to the north have median elevations greater than 500 m. In terms of median GST the regions range from Intermediate climate maturity zones in the Naoussa (16.0°C) to Hot climate maturity zones in the southern and island regions (> 19.0°C) with the Rodos the highest at 22.2°C (Table 1; Figure 2). For GST 47% of the wine regions median values fall in the Hot climate type while 30% are considered a Hot climate type. For GDD the regions have median values that range from a Winkler Region Ib for Naoussa and Amyntaion to numerous Region V (> 2222) climates. Overall all regions, median GDD values show that 20% are Region III, 30% Region IV, and 39% Region V. Median values of the HI show a similar range with the cooler regions being mostly Temperate (Naoussa and Zitsa) while the warmest regions are Very Warm on the Huglin Index (e.g., Rodos, Mosxato Kefallinias, and Agxialos). For median HI values, the Greek wine regions are predominantly Warm Temperate (53%) and Warm (33%).

While the median values give a general perspective and ranking of the climates in each region, the quantile statistics capture the spatial ranges of the indices within the regions. Given differences in elevation and distance to the coast, some regions can range across four or five index classes. For example, a northern inland location Naoussa has zones that would be considered to be too cool on all three indices while also having zones in the warmest classes on each index. For smaller, island regions with lower elevation ranges such as Santorini, the entire area falls in one index class. Furthermore, the three indices examined show strong similarity over the regions with the GST and GDD being functionally identical (r =0.99). The HI has a slightly lower correlation with the other indices (r = 0.81-0.83) and a slightly different ranking of the median index values. This is due to the HI having a day length adjustment and that it weights maximum temperatures more than GST and GDD, which ultimately better captures coastal versus inland climate characteristics. The characteristics described above have been found in other similar research for the United States (Jones et al. 2010), Europe (Jones et al. 2009), Australia (Hall and Jones, 2010), and New Zealand (Anderson et al. 2012) (not shown).

For the station analyses, lower growing season (GS) average temperatures were found at mainland stations, mainly Nemea (Tmean=18.9°C, 1934 GDD); and generally higher on the islands. GS precipitation ranged from 66 mm (Santorini) to 240 mm (Nemea) but exhibited high variability (not shown) over all locations. The majority of the climate parameters during GS exhibited statistically significant positive trends across most locations (not shown), except for DTR (negative trends in Samos, Anchialos, Pyrgos and Naoussa) and Tmax (negative trend in Naoussa). The increase of Tmin over time was the most frequently observed significant climatic trend (six out of eight cases; Figure 2). Viticulture data analysis showed a statistically significant earlier occurrence of harvest (ΔH) in five out of eight locations (Figure 2). Naoussa and Nemea exhibited positive but non-significant trends, while the island of Rodos showed grape harvest dates that were significantly delayed (0.4 days yr^{-1}) over the period examined. The harvest dates of Limnos, Samos and Santorini advanced by 0.31 to 0.55 days yr^{-1}, while the harvest dates in two mainland locations (Anchialos and Pyrgos) advanced by 0.35 and 0.77 days yr^{-1}, respectively.

Δ_H showed significant negative relations with T_{mean}, T_{min}, T_{max} and GDD for the GS period in three out of four islands (Limnos, Samos and Santorini), with increasing temperatures leading to earlier harvest (Table 2). Mainland locations (with the exception of Nemea) exhibited a similar behaviour, but more markedly in Anchialos and Naoussa. In this study, warmer growing seasons (mainly driven by increasing T_{min} and T_{max}), lead to significantly higher GDD over the time period. However, the response of harvest date to climate characteristics in this research was not uniform in all of our study locations, with island sites being slightly more affected than mainland sites. This might be explained by several reasons: (1) temperature anomalies do not affect every region in the same way (Jones et al., 2005a), (2) response to temperature changes may differ across varieties, mainly related to their temperature threshold for optimum ripening (Jones et al. 2005a), (3) grape ripeness and harvest time decision is also subject to human judgment (de Orduna, 2010) and (4) the ability of the grape growers to foresee the signs of climate change and to adapt viticultural practices that delay grape ripeness (van Leeuwen et al. 2007) may potentially mask the effect of climate change on grape ripening and minimize harvest anomalies.

4 CONCLUSION

This research has examined the spatial and temporal climate characteristics of Greek wine regions and impacts on harvest dates from trends in climate. The spatial climate assessment shows a generally warm to hot climate for viticulture, but also wide diversity of climate types across inland and elevated areas that provide the conditions to grow a wide range of varieties and produce many wine styles. Furthermore, the climate indices show similar characteristics to other regions worldwide and provide one of the first comparative assessments for Greece. For the temporal analysis, changes in Greek viticultural region climates were found to exert a significant impact on harvest timing with similar results compared to other wine regions worldwide. Warm wine regions worldwide, such as Greece, are at the upper temperature limit for many varieties and further changes in climate may push them pass suitability for viticulture producing challenges in ripening balanced fruit. To meet some of these challenges, a greater effort by growers should be given to adapt viticulture to future climate characteristics and trends, especially in the warmest areas and where early ripening varieties are currently cultivated.

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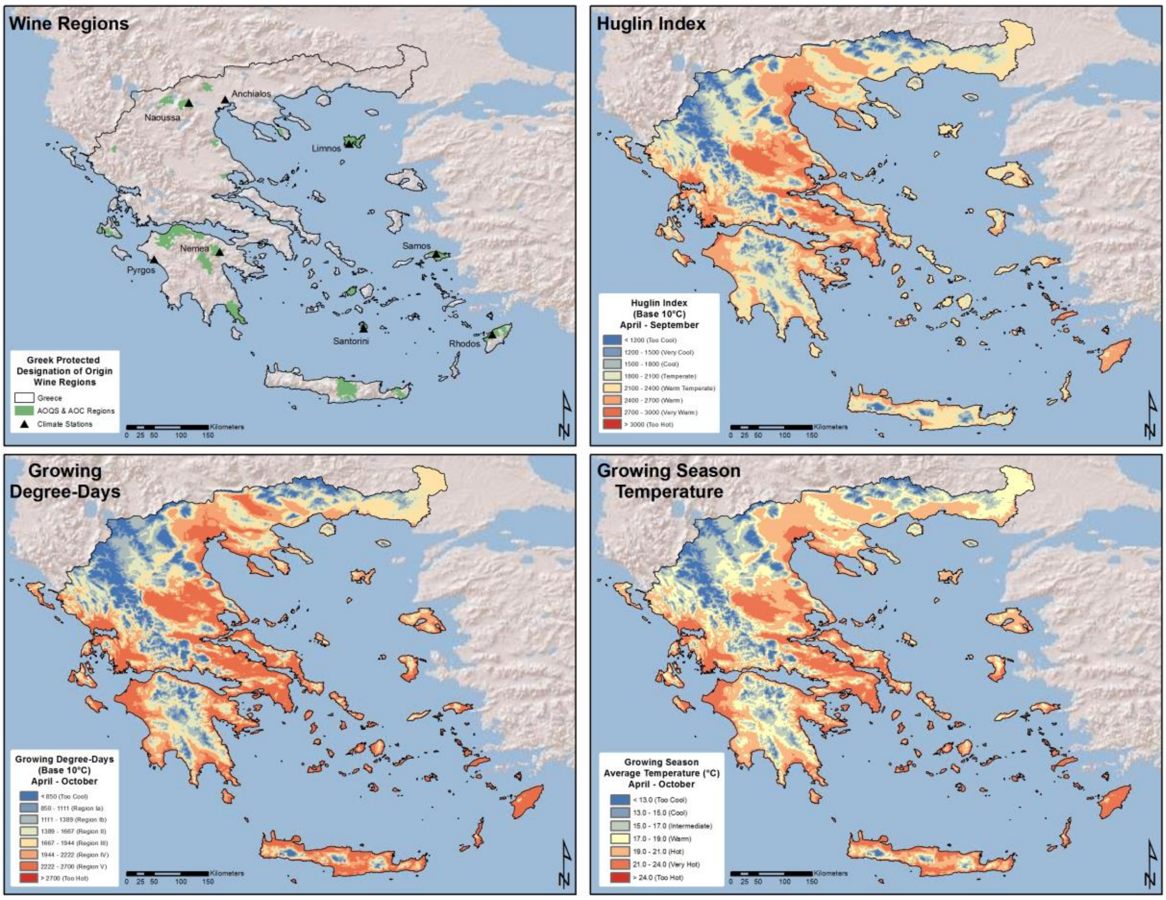

Figure 1: Greek Protected Designation of Origin wine regions: AOQS – Appellation of Origin of Superior Quality and AOC- Appellation of Origin Controlled (upper left). Maps of the Huglin Index (HI, upper right panel), growing degree-days (GDD, lower left panel), and growing season average temperatures (GST, lower right panel) over Greece.

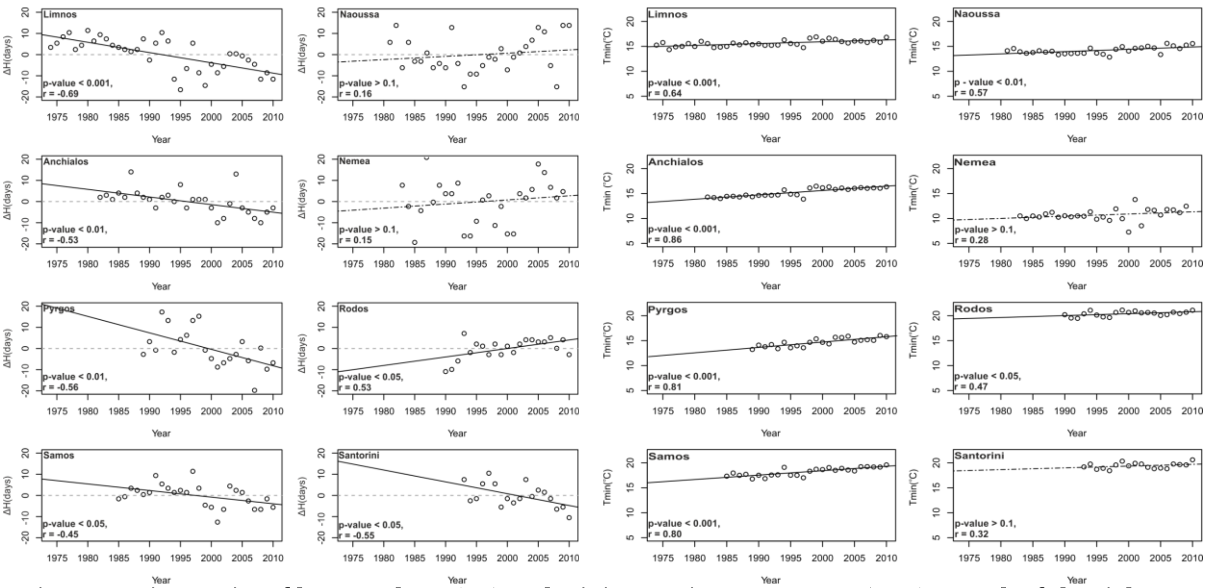

Figure 2: Time series of harvest dates (Δ_H) and minimum air temperature (T_{min}) at each of the eight locations. Solid lines indicate statistically significant trends ($p < 0.05$) while black dotted lines indicate non-significant trends ($p > 0.05$).

Table 1: Area, elevation and climate characteristics for the Greek wine regions used in the analysis. Elevation and the climate indices are given as the median averaged over each region. The table is sorted by GST from coolest to warmest median values. See text for climate index definitions.

Region*	Area (km^2)	Median Elevation (m)	Median GST (°C)	Median GDD (C° units)	Median HI (C° units)
Naousa	374.2	797	16.0	1256	1782
Amyntaion	306.5	632	16.7	1379	1939
Zitsa	92.0	596	17.0	1440	1901
Mantineia	580.1	763	17.2	1471	1951
Rompola Kefallinias	155.4	572	18.8	1838	2109
Goumenisa	209.2	295	18.9	1807	2284
Patra	1292.0	437	19.0	1838	2202
Rapsani	127.1	444	19.0	1838	2277
Nemea	388.0	460	19.4	1930	2292
Plagies Melitwna	88.3	309	19.4	1930	2184
Limnos	477.0	31	19.8	2021	2242
Maurodafni Patrwn	352.1	268	19.9	2052	2355
Dafnes	220.5	460	20.2	2112	2120
Messenikola	10.6	332	20.2	2082	2551
Mosxatos Riou	89.3	98	20.3	2113	2418
Mosxatos Limnou	477.0	123	20.3	2082	2418
Peza	97.1	406	20.5	2143	2180
Siteia Siteia Malvasia	317.5	373	20.6	2173	2179
Mosxatos Patrwn	322.6	88	20.7	2204	2448
Samos	345.4	224	20.8	2235	2414
Monemvasia Malvasia	714.2	182	21.0	2266	2406
Xandakas Candia	1202.1	308	21.0	2326	2241
Arxanai	113.5	265	21.1	2326	2242
Peza	75.3	270	21.1	2326	2242
Maurodafni Kefallinias	195.7	146	21.4	2328	2527
Paros	196.9	81	21.4	2327	2254
Santorini	89.0	64	21.8	2479	2372
Agxialos	107.4	71	21.9	2480	2799
Mosxatos Rodou	348.1	209	22.0	2449	2557
Mosxato Kefallinias	47.4	27	22.2	2480	2666
Rodos	450.1	152	22.2	2509	2558

* Note that this table shows 31 of the 35 regions as four regions overlap completely, but differ in wine type or style

Table 1: Pairwise correlations (Pearson's r) between ΔH and the climatic variables during the GS period for the eight study regions. Bold letters indicate significance at $p< 0.05$. Empty cells indicate that the respective variable was not available; 0 indicates that no days with temperature below 0°C were recorded.

	T_{mean}	T_{max}	T_{min}	GDD	DTR	Prec	T_{max}>35°C	T_{min}<0°C
Limnos	**-0.61**	**-0.64**	**-0.73**	**-0.61**	0.10	-0.01	-0.17	0.01
Samos	**-0.72**	**-0.66**	**-0.66**	**-0.71**	0.23	0.05	**-0.62**	0
Santorini	**-0.66**	**-0.64**	**-0.73**	**-0.66**	0.19	0.09	0.08	0
Rodos	0.25	0.29	0.29	0.25	0.02	-0.26	0.43	0
Anchialos	**-0.42**	-0.23	**-0.52**	**-0.42**	**0.38**		**-0.40**	0.08
Nemea	0.10	-0.19	0.07	0.10	-0.27	**0.41**	-0.17	-0.28
Pyrgos	-0.08	-0.20	**-0.56**	-0.08	0.39		-0.04	0.1
Naoussa	**-0.41**	**-0.62**	0.34	**-0.40**	**-0.62**		**-0.43**	0.03