ANALYSIS OF TEMPORAL VARIABILITY OF cv. TEMPRANILLO PHENOLOGY WITHIN RIBERA DEL DUERO DO (SPAIN) AND RELATIONSHIPS WITH CLIMATIC CHARACTERISTICS

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Abstract

The Ribera del Duero Designation of Origin (DO) has acquired great recognition during the last decades, being considered one of the highest quality wine producing regions in the world. This DO has grown from 6,460 ha of vineyards officially registered in 1985 to approximately 21,500 ha in 2013. The total grape production stands at around 90 million kg, with an average yield that approaches nearly 4,500 kg/ha. Most vineyards are cultivated under rainfed conditions. For that reason climate variability, with higher temperatures and higher water demands, may affect grape development and production. The aim of this work was to analyze the influence of the climatic characteristics on phenology within the DO. Twenty plots planted with Tempranillo (the main variety cultivated in the area) were analyzed from 2004 to 2012. The representativeness of those years was analyzed by comparing their characteristics with a longer series recorded from 1980 to 2012. The relationship between phenology and the different variables were confirmed with a multivariable analysis. While the dates during the time period showed high variability, on average, bud break was April 28th; bloom June 16th and veraison August 12th. Differences of up to 21 days in the dates were observed between years, with the earliest dates observed in dry years (2005, 2006 and to a lesser degree in 2009). On the other hand, later dates occurred in the wettest year of the period (2008). High correlations were found between veraison and temperature variables as well as with precipitation-evapotranspiration recorded during the bloom-veraison period. These effects tended to be higher in in the central part of the DO.

Keywords: climate change, grapes, phenology, spatial and temporal variability, Tempranillo, water deficit

1 INTRODUCTION

Climate change represents a major challenge for agriculture and especially viticulture and wine production. Increasing temperatures and evaporative demands affect both yield and quality, potentially requiring changes in vineyard management or the adoption of new varieties that are better suited to the new climate. Different simulations have been carried out to predict the effect of temperature changes on grapevine phenology, physiological processes and vine water conditions (Bindi et al. 1996, Pieri et al. 2012, Rubino et al. 2012, Jones 2012, among others), which have important consequences on grape ripening and the resulting wine quality. The effects may be different depending on the region of production and the varieties grown.

Vineyards in the Ribera del Duero area (Spain) date back to the Roman period, with significant fluctuations in production throughout the centuries. The history of viticulture in the Ribera del Duero is strongly tied to the landscape, climate and culture. During the 10th and 11th centuries vineyards in the area were consolidated into larger operations and achieved relatively stable production. Over the following centuries, vineyards and wine production became an increasingly important aspect of the economic and cultural development of the Ribera del Duero spreading to other Spanish areas. The present DO Ribera del Duero was established in 1982 and has become world renowned for being one of the highest quality red wine producers.

The main purpose of this research was to investigate the spatial variability of climate and its trends and effects on phenology within the Ribera del Duero Designation of Origin (Ribera del Duero DO). The climate characterization was made based on daily temperature and precipitation series recorded from 1980 to 2012 at five locations along the Duero River within the DO. Phenology was observed during the period 2004-2012 at 20 plots distributed throughout the Ribera del Duero DO area and planted with Tempranillo. Phenology was related to different bioclimatic indices commonly used in viticulture research.

2 MATERIALS AND METHODS

2.1. Study area

The Ribera del Duero DO covers approximately 115 km along the Duero River, from Quintanilla de Onésimo (Valladolid) to San Esteban de Gormaz (Soria) (Figure 1), with a vineyard surface of roughly 21,500 ha. Geologically the Ribera del Duero is part of the large septentrional plateau formed by a large basement filled with Tertiary deposits. Most of these deposits consist of layers of loamy and sandy ochre and red clays and terraces from the Duero River. The main soil types in the Ribera del Duero area are *Typic Xerofluvent* (in the tertiary deposits), and *Typic Xerochrept, Calcixerollic Xerochrept* and *Calcic Haploxeralf* (in the mean and low Duero terraces). The climate is temperate with dry or temperate summers in the western portion of the DO and temperate with a dry summer season in the eastern portion of the DO. The mean annual temperature ranges 10.2-12.0ºC, with mean maximum temperatures around 18.4ºC and mean minimum temperatures ranging between 4.5 and 5.0ºC. The mean annual precipitation ranges between 413 and 519 mm with the main rainfall periods in April-May and October-November-December.

2.2. Climate data and analysis

For this analysis, daily temperature and precipitation data for the period 1980-2012 from five stations belonging to the AEMET were used: Retuerta (RET); Valbuena de Duero (VD); Roa de Duero (ROA); Aranda de Duero (AD); San Esteban de Gormaz (SEG) (Figure 1). Elevations over these locations ranged from 735 m to 790 m. For each observatory the following indices were evaluated:

- Growing season (April-October) temperature [maximum (TGSmax); minimum (TGSmin); mean (TGSm)]
- Number of extremes: number of frost days (FD) and number of days with T > 30ºC (NDT30)
- Bioclimatic indices: Winkler index (WI) = Σ ((Tmax+Tmin)/2)-10°C) and Huglin index (HI) = Σ ((Tavg-10°C) + (Tmax-10°C)/2)*d
- Daily temperature range (DTR = Tmax-Tmin) during the ripening period (August-September)
- Annual precipitation: for the period November- October ($P_{HY}An$)
- Growing season precipitation (April-October) (PGS) and precipitation in each phenological stage [bud break-bloom (PBB), bloom-veraison (PBV), veraison-harvest (PVH)]
- Vine growing season evapotranspiration estimated according to Penman Monteith equation and using the crop coefficients proposed by Allen et al. (1998) (ETcGS).

Annual means and standard deviations were calculated for each location and an ANOVA was done to identify significant differences throughout the Ribera del Duero area. In addition, for each location a temporal analysis was carried out in order to evaluate changes and trends of the different climatic variables and indices. The significance of the trend analyses were analyzed using the Mann Kendall test (Libiseller and Grimvall, 2002). In addition, the spatial variability of all these indices as well as their trends were analyzed.

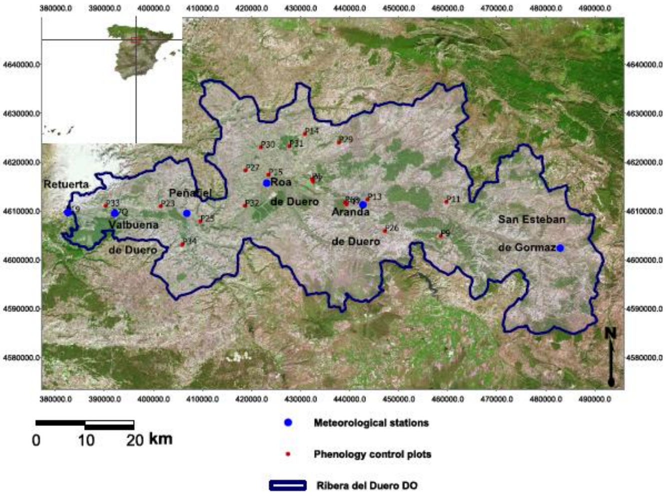

Figure 1: Location of meteorological stations and phenology control plots.

2.3. Phenology data and analysis

Twenty plots distributed throughout the Ribera del Duero area (Figure 1) and planted to the Tempranillo variety were analyzed for the period 2004-2012 from data provided by the Consejo Regulador of Ribera del Duero DO. Phenology dates (Baggiolini classification) corresponding to the C (bud break), G, I (bloom), K, L and M (veraison) stages were averaged over each plot and analyzed. In order to characterize the spatial variability a classification of the plots was done using a hierarchical clustering technique, using Ward's minimum variance method, taking into account the dates referring to the stages C, G, I, L and M across all plots. The average values of each variable for the years included in each cluster and the influence of climate variables on phenology were analyzed. A factor analysis including temperature and precipitation indices as well as phenological dates was applied to the different groups of plots for which differences in phenology was previously established. The variables included in the factor analysis were growing season temperatures

(TmaxGS, TminGS, TmGS), precipitation-evapotranspiration (for the growing season PGS, and each phenological stage-PBB, PBV, PVH) and different bioclimatic indices (WI, HI, DTR).

3 RESULTS AND DISCUSSION

3.1. Climate variability among the analyzed observatories

Table 1 shows the average and standard deviation of temperature variables and bioclimatic indices for each location for the period 1980-2012. There were significant differences in mean Tmax between the stations located at both extremes of the area (RET and SEG) with the lowest temperatures recorded in the eastern part of the Ribera del Duero. Significant differences were also observed for minimum temperatures between AD and SEG but no differences were found among the rest of the locations.

The mean number of FD revealed high variability from year to year, with a maximum of 118 days and a minimum of 65 days per year. Maximum extreme temperatures also showed significant differences between both extremes of the area with mean values ranging between 52.9 and 43.1 days per year, and a maximum of 81 days per year. The ROA location exhibited the highest values of warm extremes and the minimum number of frost days. The differences in mean temperatures, frost risk and precipitation found in this analysis are in agreement with the general traits shown in previous work by Gómez-Miguel (2003). The mean DTR for the ripening period presented significantly higher values in RET compared to ROA, but showed no differences elsewhere. The differences in the WI among locations (between 1250 and 1311) were not significant. However, significant differences in the mean HI (between 2026 and 2219) existed between both extremes of the DO. Similar spatial variation was found for crop evapotranspiration.

Table 1: Mean and standard deviation for temperature variables for each location during 1980- 2012.

	Location	Retuerta (RET)	Valbuena de Duero (VD)	Roa de Duero (ROA)	Aranda de Duero (AD)	San Esteban de Gormaz (SEG)
	TmaxGS(ºC)	25.49 ± 1.16 a	25.13 ± 1.07 ab	25.23 ± 1.27 ab	25.25 ± 0.89 ab	24.76 ± 098 b
	TminGS (ºC)	8.79 ± 0.86 ab	8.99 ± 1.17 ab	8.83 ± 0.61 ab	8.63 ± 0.80 a	9.11 ± 0.83 b
	TmGS (ºC)	17.12 ± 0.81 a	17.08 ± 1.02 a	17.02 ± 0.77 a	16.95 ± 0.74 a	16.89 ± 0.78 a
	DTR (ºC)	18.1 ± 1.9 a	17.1 ± 1.3 b	16.8 ± 1.4 b	17.7 ± 1.4 ab	17.7 ± 1.4 ab
	FD (days)	85.8 ± 17.8 a	76.9 ± 19.6 ab	68.8 ± 16.9 b	87.4 ± 19.9 ab	82.7 ± 16.7 ab
	NDT30(days)	52.9 ± 13.7 a	47.8 ± 14.7 ab	51.8 ± 12.4 ab	48.5 ± 12.8 ab	43.1 ± 10.8 b
	WI (dgd)	1311 ± 173	1299 ± 219	1287 ± 163	1272 ± 152	1250 ± 155
	HI (dgd)	2119 ± 181 a	2081 ± 197 ab	2084 ± 192 ab	2076 ± 144 ab	2026 ± 162 b
	ETcGS (mm)	598.1 ± 66.5 a	580.2 ± 23.2 ab	588.0 ± 43.4 ab	595.4 ± 64.7 ab	565.9 ± 25.8 b
Change ratio	TmaxGS	0.0254	0.0288	0.011	0.006	0.0316
	TminGS	**0.0455**	**0.0231**	0.011	0.0128	**0.0262**
	TmGS	**0.0332**	**0.0288**	ns	0.011	**0.0326**
	DTR	-0.044	-0.288	-0.317	-0.31	ns
	FD	**-0.523**	0.597	**-0.534**	-0.2747	-0.30
	NDT30	ns	ns	ns	ns	ns
	WI	**6.193**	**4.963**	1.865	2.700	**5.100**
	HI	**6.949**	**5.957**	3.065	2.746	**6.733**
	ETcGS	1.854	0.598	0.648	1.700	0.644

- different letters mean significant differences at 95% level. Bold letters indicate significant trends at 95%.

Significant increases in temperature were observed at the stations located at both extremes of the DO, but not in the central part of the region. Minimum temperature during the growing season increased significantly in RET, VD and SEG, along with a decreasing number of frost days. The maximum temperature trends during the growing season were not significant in any location. The WI and HI increased accordingly with significant trends in RET, VD and SEG but not for the rest of the locations (Table 1). The average increase in temperatures (about 0.03 ºC per year for the last 30 years) as well as the changes observed in the bioclimatic indexes (WI and HI) in some locations are in agreement with observations in other viticultural areas of Spain (Ramos et al. 2008; de Herralde, et al. 2010; Lorenzo, et al. 2013) although the changes were greater at both extremes of the area (east and west) and lower elsewhere. In other regions around the world trends in temperatures and heat-related variables have shown similar trends (Duchêne and Schneider 2005; Jones and Goodrich 2008; Makra et al. 2009; Webb et al. 2011; Santos et al. 2012; Jones 2012; Hannah et al. 2013; among others).

Statistics and trends for average annual and growing season precipitation for each location are shown in Table 2. During 1980-2012 high year to year variability in precipitation was recorded. For annual precipitation the mean values ranged between 345.9 mm and 472.2 mm, with differences among years greater than 400 mm. Precipitation recorded during the growing season ranged between 144.9 and 231.9 mm, which on average represents between 43 and 49% of annual precipitation. Significant differences were found between the extremes of the Ribera del Duero area and also between VD and the rest of locations. These lower values were also confirmed for a shorter series recorded in Peñafiel (15 km east) for the last 10 years.

Within the growing period, more than 50% of precipitation fell during the bud break-bloom period. Precipitation during the bloom-veraison and veraison–harvest periods is relatively low (about 20-24% of growing season precipitation in each period). Significant differences were found between growing season precipitation recorded in some stations located at both extremes of the DO (western and eastern part). Additionally, in four of the five locations decreasing precipitation trends during the bud break-bloom and bloom-veraison periods were found. These trends were in agreement with those observed in other Spanish regions for spring (Ramos et al. 2012; De Luis et al. 2009). This implies decreasing precipitation in some crop stages where increases in temperature will likely give rise to greater water deficits and potentially negative impacts for grape development.

Table 2: Mean and standard deviation for precipitation variables for each location during 1980- 2012.

Location		Retuerta (RET)	Valbuena de Duero (VD)	Roa de Duero (ROA)	Aranda de Duero (AD)	San Esteban de Gormaz (SEG)
$P_{HY}An$ (mm)		403.5 ± 120.2 a	345.9 ± 100.8 b	417.8 ± 95.6 a	422.1 ± 94.5 a	472.2 ± 103.8 c
PGS (mm)		178.9 ± 73.4 a	144.9 ± 57.2 b	184.3 ± 62.4 a	199.4 ± 63.1 a	231.9 ± 76.6 c
P BB (mm)		104.2 ± 55.3 ab	83.1 ± 47.2 a	101.3 ± 49.4 ab	110.9 ± 46.6 ab	133.9 ± 56.1 b
P BV (mm)		38.1 ± 28.1 ab	30.6 ± 22.4 a	41.9 ± 26.5 ab	48.1 ± 36.9 ab	53.3 ± 33.6 b
PVH (mm)		36.5 ± 23.5 ab	31.2 ± 19.9 a	41.0 ± 21.9 ab	40.4 ± 22.9 ab	44.7 ± 28.1 b
Change ratio	PGS	-1.10	1.296	-1.208	-1.728	ns
	PBBB	ns	ns	ns	ns	ns
	PBB	**-0.350**	**0.3265**	**-0.466**	ns	**-0.43**
	PVH	**-0.734**	**0.505**	**-0.666**	**-0.855**	**-0.44**

- different letters mean significant differences at 95% level. Bold letters indicate significant trends at 95% level.

3.2. Phenology variability

Table 3 shows the average dates for different phenological stages recorded during 2004-2012. On average bud break occurred April 28th while bloom averaged June 16th and veraison averaged August 12th. During this time period the phenology exhibited high variability with differences between plots and between years. Differences in the dates between years of up to 21 days were observed with the earliest dates observed in dry years (2005, 2006 and to a lesser degree in 2009). On the other hand later dates occurred in the wetter years, especially in 2008. Within the region the 20 plots were classified into three groups according to the mean phenological dates with differences of 2-3 days for all dates on average. The plots located in the western part of the DO typically experience earlier phenology, particularly with stages G through M. For the remainder of the plots there were differences between locations on the terraces of the river and those located at higher elevations which exhibited a delay in phenology.

Table 3: Mean dates and standard deviations of different stages for each year averaged over all plots.

	Stage C Bud break		Stage G		Stage I Bloom		Stage L		Stage M Veraison	
	mean	std (days)	mean	std (days)	mean	std (days)	mean	std days)	mean	std (days)
2004	29-Apr	4.8	26-May	3.2	20-Jun	3.8	13-Jul	6.6	11-Aug	4.6
2005	30-Apr	2.6	16-May	4.6	8-Jun	2.9	6-Jul	3.0	3-Aug	1.9
2006	25-Apr	3.7	12-May	4.9	8-Jun	3.8	18-Jul	6.0	2-Aug	2.5
2007	1-May	2.9	20-May	7.2	22-Jun	6.3	22-Jul	1.7	21-Aug	2.7
2008	29-Apr	5.9	27-May	4.5	28-Jun	3.6	11-Jul	3.5	23-Aug	2.1
2009	5-May	4.0	21-May	4.6	15-Jun	2.7	23-Jul	4.1	9-Aug	3.6
2010	27-Apr	1.8	20-May	7.0	21-Jun	4.4	6-Jul	4.6	18-Aug	4.1
2011	15-Apr	4.4	8-May	5.6	7-Jun	2.7	5-Jul	3.3	9-Aug	3.5
2012	4-May	6.2	29-May	2.6	18-Jun	2.8	16-Jul	4.5	13-Aug	5.6
2004-2012	*28-Apr*	*5.9*	*20-May*	*7.1*	*16-Jun*	*7.3*	*13-Jul*	*7.1*	*12-Aug*	*7.4*

The results of the cluster analysis for precipitation and temperature during 1980-2012 identified 4 groups. Cluster 1 grouped the wet years, with an average PGS=274 mm, a PA=490.8 mm and ETcGS=558.9 mm and represents 15.15% of the years. Cluster 2 grouped 33.33% of years and corresponded to the driest years, with an average PGS=13.7 mm, PA=412.3 mm and ETcGS=598.6 mm. Cluster 3 exhibited intermediate characteristics: greater PGS than group 2 (204.1mm), but lower PA (400.0 mm) and also lower ETcGS (575.1 mm). Finally, cluster 4 included only 2012, which was separated from the rest due to its extreme characteristics: PGS=160 mm, but PA was very low (267) and ETcGS was very high 796 mm.

Temperature variables for each year during the time period were also classified into four groups. Cluster 1 represents the coolest years, with a mean Tmax=21.35 ºC and a mean Tmin=13.88 ºC (18.18% of the years). Cluster 1 also had the lowest NDT30=36.4 days among the groups. Cluster 1 was highly related to cluster 4 in the precipitation/evapotranspiration classification, including 2007 and 2008. Cluster 2 represented 21.21% of total years with slight warmer conditions than cluster 1: Tmax=22.13 ºC, Tmin=14.53ºC and NDT30 was also greater (NDT30=38.1 days), while the DTR was smaller (17.66 *vs* 18.85 ºC). Cluster 3 is warmer than the previous clusters (Tmax=22.58 ºC; Tmin=16.56 ºC, NDT30=45.8 and TRD=19.54), but also in that the differences between Tmax and Tmin were also higher as well as the number of days with extreme temperatures. Within cluster 3 the years 2010, 2011 and 2012 were included. Finally, cluster 4 represented 22 % of years (2003, 2005, 2006 and 2009), grouping the years with the highest temperatures (Tmax=23.3ºC; Tmin=18.01ºC) and a high number of warm extremes (NDT30=50.5 days). The daily temperature range, however, was smaller than in cluster 3, which means similar increase of both Tmax and Tmin during the ripening period. Clusters 3 and 4, representing the highest temperatures, were also in correspondence with the precipitation/ evapotranspiration clusters with greater deficits (clusters 2 and 4), due to small rainfall and high evapotranspiration.

The relationship between phenology and the different climate variables were confirmed with a multivariable analysis. Table 3 shows that the differences in phenology among years were smaller in the earlier stages than in the later stages of the growing season (veraison). The relationships between M stage (veraison) dates and climate parameters obtained for the three groups of plots established in the previous analysis are shown in Table 4. Three factors described more than 85% of variance for the three areas. F1 was associated with maximum temperatures, WI and HI; while the other two factors (F2 and F3) were associated with water availability (precipitation-evapotranspiration) in each phenological stage, FD and DTR. However, the variables included in each group were not the same for the three areas. For the western part of the DO, veraison dates were only influenced by temperature variables with the results indicating an earlier veraison when all climatic variables associated with factor F1 increased. However, for the plots located in the central part of the DO, veraison dates were also influenced by water accumulated in the soil during the bloom-veraison period (F1) and during the dormant period (F3); and by the decrease in frost days (F3). The effects of temperature were greater in the plots located on the river terraces, while the effect of available water was higher on the plots located at higher elevations. The analysis of the influence of available water (P-ETc) on phenology showed that water deficits during the bloom-veraison period had higher effects on dates in the central part of the DO (8 and 14 days advanced for 100 mm of water deficit in the river terraces, and between 12 and 20 days for 100 mm water deficit in the plots above the terraces).

Most analyses relating phenology with climate change have focused mainly on the impacts of temperature changes on phenological events and on the suitability to different winegrape cultivars to those changes. Different authors have highlighted the advance of harvest dates and dates of other phenological stages with increasing temperatures (Ganichot 2002; Duchêne and Schneider 2005; Dalla Marta et al. 2010; Jones and Davis 2000; Nemani et al. 2001, among others). However less attention has been paid to the effects of water availability derived from higher evapotranspiration, particularly when precipitation is projected to decrease. The results observed in this study are in agreement to those found in other Spanish viticultural areas located in NE Spain that were related to water impacts (Camps and Ramos 2012).

Table 4: Factor analysis of veraison dates and climatic variables for three areas within the DO: A) western part of DO; B) central part of the DO on the river terraces; C) central part of the DO on hillsides.

	A			B			C		
	F1	F2	F3	F1	F2	F3	F1	F2	F3
Stage M	**-0.877**	0.064	0.051	**-0.701**	0.336	0.403	**-0.687**	0.490	0.290
TmaxGS	**0.984**	0.042	0.022	**0.886**	0.339	0.005	**0.890**	0.332	-0.020
TMinGS	**0.645**	0.226	0.652	**0.732**	-0.234	0.489	**0.765**	-0.184	0.433
TmGS	**0.897**	0.149	0.372	**0.934**	0.278	0.080	**0.937**	0.273	0.034
DTR	0.008	0.109	**-0.690**	0.257	**0.848**	0.191	0.242	**0.834**	0.183
FD	-0.238	-0.259	**-0.636**	-0.035	0.003	**-0.722**	0.004	0.084	**-0.780**
NDT30	**0.603**	-0.019	0.512	0.807	0.220	0.159	**0.864**	0.114	0.161
WI	**0.895**	0.077	0.389	**0.950**	0.205	0.047	**0.952**	0.205	0.017
HI	**0.972**	0.098	0.164	**0.907**	0.302	0.069	**0.911**	0.296	0.034
P-ETcD	0.143	0.950	0.007	-0.080	-0.041	**-0.774**	-0.096	-0.124	**-0.736**
P-ETcBB	-0.244	-0.927	0.021	**-0.725**	-0.240	0.511	**-0.758**	-0.232	0.481
P-ETcBV	-0.283	0.870	0.168	-0.237	-0.864	0.213	-0.272	-0.822	0.269
% variance	50.9	21.4	10.1	51.6	15.9	13.2	52.5	15.1	13.8

4 CONCLUSION

This research has examined the spatial and temporal climate characteristics and relationships with grapevine phenology for the Tempranillo variety in the Ribera del Duero DO of Spain. The region experiences an intermediate to warm climate type on growing season average temperatures (16.9-17.1°C), is a Region Ib on the

Winkler Index (1250-1311 GDD), and temperate to warm temperate on the Huglin Index (2026-2119 HI). The region is moderately dry with 346 to 472 mm annually, with the growing season of April through October receiving between 43 and 49% of the annual precipitation. While the phenological dates during the time period showed high year to year variability, bud break in the region occurs April 28th on average; while bloom averages June 16th and veraison averages August 12th. Over the region spatial differences in climate and phenology are seen between the western, central and eastern parts of the Ribera del Duero DO with the western locations generally warmer and earlier. While there is high variability year to year, increasing trends in minimum temperatures, bioclimatic indexes (WI and HI), and a decreasing number of FD have been observed in the region. Strong relationships between climate, available water and phenology have been documented in this research, with especially important roles of increasing temperatures and bloom to veraison water deficits producing advanced phenology in all areas, but especially in the central part of the DO. Understanding relationships between climate and grapevine phenology over a region are useful to continually assess the role that climate variability and change play in vine growth, fruit production and quality.

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