

Macabeo (Viura) grape response to climate variability in areas located at different elevations in the Rioja Designation of Origin

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Abstract

BACKGROUND: This research aims to analyse the influence of climatic conditions on phenology and grape composition of Macabeo, which is one of the white varieties authorized in Rioja DOCa. Phenological dates for flowers separated and harvest, and grape composition were evaluated for the period 2008–2020 in five plots, located at different elevations (457–650 m a.s.l.). Grape parameters were related to temperature and water deficit recorded along the growing cycle.

RESULTS: High variability in the weather conditions were recorded during the period analysed, with differences in the average growing season maximum temperature of up to 2.5 °C among years and about 2 °C among locations. Differences in the average growing season precipitation of about 200 mm among years and up to 60 mm among locations were recorded. That high variability could explain the differences in grape composition observed among years and among zones. The lowest sugar contents were recorded at the highest elevation, while acidity in that area was the highest. Although the relationship was only significant in one plot, probable volumetric alcoholic degree increased with increasing maximum temperature. Titratable acidity and malic acid decreased with increasing maximum temperature, the change being higher in the plots located at the highest elevation. Both titratable acidity and malic acid were significantly affected by water deficits recorded during the growing season, and in particular that recorded after flowering.

CONCLUSION: The results indicate that under warmer scenarios a decrease in titratable acidity and in malic acid might be expected for this variety, but with differences among zones located at different elevations.

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Keywords: malic acid; phenology; temperature; titratable acidity; water availability

INTRODUCTION

Vines might suffer significant impacts under climate change, although these impacts differ depending on the variety. During the last decades, several studies carried out in different viticultural areas have shown the effect of temperature trends on phenology.^{1–6} In these referred works, the authors observed an advance of the phenological timing and a shortening of the periods between phenological events, with the consequent advance of harvest. The degree of change, however, may be modulated by other aspects such soil characteristics and water availability,^{7–9} elevation^{10,11} or management practices.^{12,13} In addition, and associated with the changes in phenology, weather conditions also influence grape composition and quality.^{3,12,14–16} All these effects, however, can differ between cultivars. Some cold days are needed to cover chilling hours but later frost may represent a risk for the correct growth, and during the growing season grapevines need sustained average daily temperatures above a threshold to initiate growth and then sufficient heat accumulation to reach maturation. However, extreme temperatures during berry growth can have negative impacts on grape development due to the effects

on transpiration, stomatal conductance and photosynthesis reduction, premature veraison, berry abscission, enzyme activation and less flavour development.^{17,18} In addition, under rainfed conditions, the amount of rainfall and its distribution during the growing season conditions the availability of water, which can be the main challenge to reach adequate quality grapes at ripening and sustainable yield. The climatic conditions are affected by elevation, which is an additional point to consider in the vine response. Lower temperature and wetter conditions can be expected at higher elevation, which could be favourable conditions under warmer scenarios. However, the risk of exposure of vines to excessive UV-B radiation can be noteworthy at high

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elevation,¹⁹ which may affect berry composition quality.²⁰ Climate variables (temperature, precipitation, evapotranspiration) together with additional related indices (bioclimatic indices) can help in viticultural zoning to define differences in the suitability of a wine-growing area and for specific cultivars.²¹

Each viticultural region, in particular those regulated under a designation of origin, establishes the cultivars in each area, corresponding in most cases to those that have been grown traditionally in their vineyards. Each cultivar is suited to a given temperature range,²² but under the expected warmer conditions associated with climate change scenarios the suitability of each cultivar may change, giving rise to productivity losses.²³ This could affect the economy of the area, particularly when the wine sector is one of the main drivers for the region. In this context, there is a need to analyse the response of the current cultivars to different weather conditions, to know their potential under warmer situations that may occur.

This research was carried out in the Qualified Denomination of Origin 'Rioja' (DOCa Rioja), located in the north of Spain, close to the Ebro River, which covers about 65 700 ha (www.riojawine.com). Vines are planted at elevations between about 300 m a.s.l. (terraces from the river) and more than 700 m a.s.l. on soils classified as Inceptisols (mainly Calcixerolic Xerochrept) and Alfisols (Petrocalcic Calcixerolic, Calcic Haploxeralf, Typic Xerorthent, Litic Xerorthent and Litic Palexeralf).^{24,25} The average temperature in the growing season in the region varies between 16.0 and 18.8 °C, with maximum temperatures in the same period between 23.4 and 26.1 °C, the highest temperatures being recorded in the zones located at the lowest elevation. The annual precipitation is about 420 mm, with about 50% recorded in the growing season.²⁶

The wine sector of Rioja is the main economic driver in the region, producing about 270 ML of wine annually. Ninety percent of the surface area is cultivated with red varieties, with Tempranillo being the dominant variety (78.8% of the total surface); among the white varieties, which represent the remaining 10%, Macabeo is the majority variety (6.16% of the total surface).

Previous studies have been carried out in Rioja DOCa on the main red cultivars (Tempranillo, Grenache and Graciano),^{11,26,27} but less attention has been paid to white cultivars, which are also authorized and grown in the area. The results of these previous analysis have shown that the cultivars with earlier phenology

may suffer higher impacts in phenology and in grape composition under warming climates than those with later phenology and, given that white cultivars may have earlier timing than red varieties, they could also suffer negative impacts. In this respect, Barnund et al.²⁸ indicated an expected higher effect on Chardonnay than on Shiraz, Cabernet Sauvignon or Tempranillo. However, under warmer conditions than those existing in the study area, Chacón-Vozmediano et al.²⁹ projected higher negative effects in Tempranillo compared to Chardonnay. In order to deepen this knowledge, the aim of this work was to evaluate the response of the white cultivar occupying higher surfaces in the study area (Macabeo, known in La Rioja by the synonym Viura). This cultivar, with its origin in Spain, is the second most cultivated white grape variety in Spain³⁰ and has increased its cultivated surface in the last decades. It is also cultivated in southern parts of Languedoc-Roussillon in France. It is highly productive and gives rise to fruity wines with remarkable acidity. This grape variety has a late bud-break and late harvest, and it is cultivated in hot and dry regions, but it is not recommended in wet environments or in zones with very dry soils, as it can suffer senescence and premature leaf fall. Macabeo is used for both young and aging wines as well as for the production of sparkling wines.

As previously commented, each cultivar can have different thermal requirements and therefore may be affected in different ways by changes in temperature. The fact of being cultivated in warm and dry conditions could indicate their potentiality under warmer situations, but a detailed analysis is needed. Thus, under this hypothesis, the aim of this research was (a) to evaluate the variability in the phenological response and in grape composition of the Macabeo cultivar under different weather conditions recorded in the last decades at different elevations in the Rioja DOCa, and (b) to evaluate the climatic variables and periods during the growing cycle that have a greater influence on its response.

MATERIALS AND METHODS

Study area

This research was based on the information collected in five locations of the Rioja DOCa (Haro, H; San Asensio, SA; Cenicero, C; Alesanco, A; Sotés, S) which are located between 457 and 650 m a.s.l. (Fig. 1). The soil properties of the studied plots are shown in

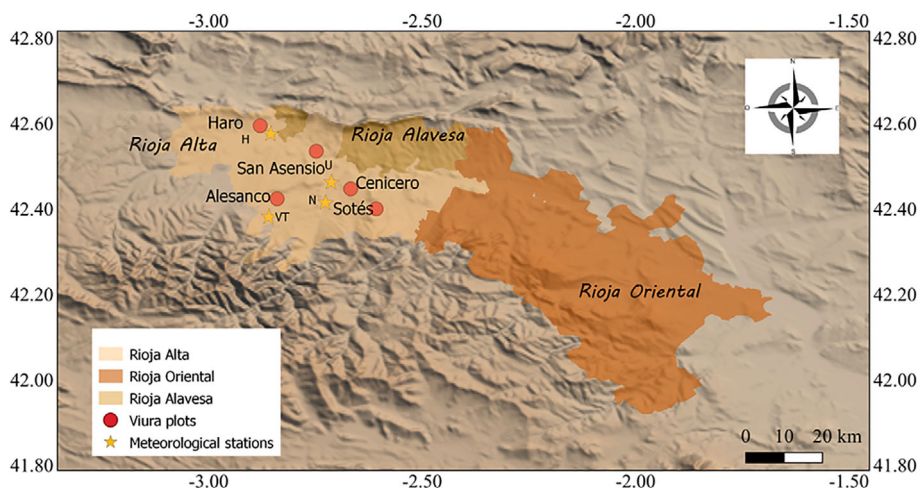


Figure 1. Location of plots and meteorological stations in the study area.

Table 1. Soil surface properties of the plots included in the study (soil particle distribution (USDA) and organic matter content (OM))

Plot	Year plantation	Elevation (m a.s.l.)	Clay (g kg ⁻¹)	Silt (g kg ⁻¹)	Sand (g kg ⁻¹)	Coarse elements (g kg ⁻¹)	OM (g kg ⁻¹)
H	1975	480	235.7	422.0	342.3	152.6	19.3
SA	1984	457	258.8	434.6	306.6	144.6	12.6
C	1977	560	212.3	413.9	373.8	140.1	10.2
A	1990	600	257.1	433.1	309.8	126.7	17.4
S	1965	650	297.3	423.6	279.1	171.1	14.6

Table 1. The soils have organic carbon content that varies between 10.2 and 19.3 g kg⁻¹; clay content that ranges between 212.3 and 297.3 g kg⁻¹; silt content between 413.9 and 434.6 g kg⁻¹; and sand content between 279.1 and 373.8 g kg⁻¹, while the coarse fraction varied between 126.7 and 171.1 g kg⁻¹ (information obtained from the European Soil database (ESDAC)).

Vine information

The vineyards analysed were planted with Macabeo between 1972 and 1990. The vines were goblet-trained in a frame, in agreement with the regulations established by the Consejo Regulador of Rioja (3250 vines ha⁻¹ with an average pattern of 2.8 m × 1.1 m) and vines were not irrigated. The phenological dates referred to flowers separated (stage H according to Baillod and Bagiollini³¹), and harvest (usually based on sugar content and acidity) recorded in each plot were evaluated for the period 2008–2020. The information for the phenology referred to the dates at which 50% of the plants in the survey plots reached the phenological stage. The information referred to other stages were not available for all plots and years, but the average values of the available information was used to consider the starting point of the growing cycle (stage C – budbreak – on 15 April, on average) and to define the onset of ripening (stage M – veraison, on 15 August, on average). Grape composition included total sugar content (expressed as probable volumetric alcoholic degree (PVAD)), pH, titratable acidity (AcT), malic acid (AcM) and berry weight (BW) during ripening for the same period. Grape sampling was carried out by collecting berries in 40 randomly selected plants, at a rate of one cluster per plant and five berries per cluster from different parts (upper, central and lower parts of the cluster). All grape parameters were supplied by the Consejo Regulador of Rioja DOCa and they were analysed following the methods recommended by the OIV.³²

Weather information

The weather conditions recorded during the period analysed were taken from meteorological stations belonging to the Rioja Government and they were located close to the analysed plots (Fig. 1). Daily temperature (maximum (Tmax) and minimum (Tmin)) and precipitation (P) recorded in each year as well as the reference crop evapotranspiration (ETo, estimated according to Penman Monteith equation) were averaged for the growing season (GS: budbreak–harvest). The crop evapotranspiration (ETc) was estimated using the crop coefficients proposed by Allen and Pereira,³³ and the P-ETc index (precipitation minus crop evapotranspiration) was defined to estimate water availability. The information related to the different variables was used to analyse the relationship between the vine response and the weather conditions. The projected changes in temperature for the zones, where the plots were located, which have been evaluated in

previous research,¹¹ were taken into account together with the variability observed during the period analysed to make some future projections. Those projections were estimated taking into account the projected changes in the climatic variables and the values corresponding to the growing season and their relationships between grape parameters and the mean variables obtained in the regression analysis.

Data analysis

The differences in the phenological response as well as in the grape composition among locations were analysed with a means test. The trend in the phenological dates were evaluated using the Mann–Kendall test.³⁴ The similarity in response among the analysed locations was evaluated year by year using a hierarchical cluster analysis, based on grape composition at harvest and the date at which it was carried out. This allowed establishing zones with different responses at different elevations. The Ward method was selected and the Euclidean distance was used to evaluate the similarity in the response of the different locations. For each group of plots, the effect of climatic variables referring to different periods during the growing cycle on grape composition was evaluated by factor analysis (FA). Mean maximum and minimum temperature and precipitation in periods between flowers separated and harvest (periods between stage H and M, and between stage M and harvest) were included in the analysis. Principal component analysis (PCA) was used to extract the factors and varimax rotation to maximize the sum of the variance of the squared loadings. The differences in grape composition among years with different characteristics were considered to predict potential changes under climate change scenarios. The analysis was done using Statgraphics XVI (Statgraphics Inc., Warrenton, VA, USA).

RESULTS

Spatial and temporal variability

The variability in the weather conditions, as well as in the phenology and in grape composition of the Macabeo variety at the different locations of the Rioja DOCa, are presented in this section.

Variability in the weather conditions

The average maximum and minimum temperature (TmaxGS and TminGS) and precipitation (PGS) in the growing season recorded at each location during the period analysed are shown in Fig. 2. The average TmaxGS ranged between 23.7 and 25.6 °C and with a range of up to 3.4 °C within the period analysed. Regarding the TminGS, the average value varied between 10.3 and 11.4 °C, with a range of up to 2.3 °C within the period analysed. The PGS was in general scarce (average values <225 mm) but with high variability from year to year (between less than 100 mm and more than 360 mm). The PGS represented between 30% and 50% of the annual precipitation, on average.

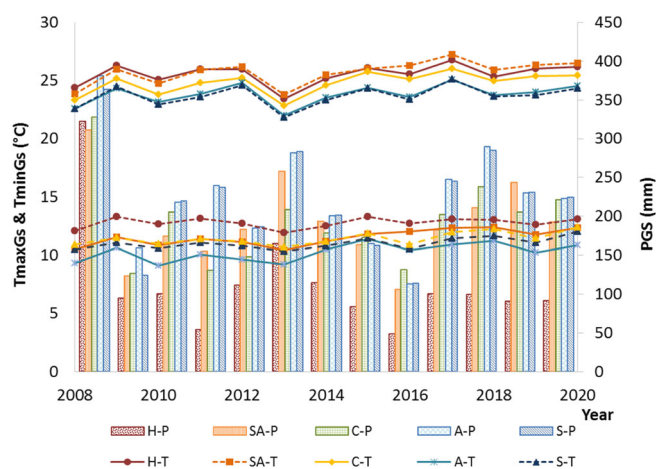


Figure 2. Mean growing season maximum and minimum temperatures and precipitation at different locations referred to the period 2008–2020.

Variability in phenology

During the period analysed, there was high variability in the phenological dates corresponding to the stage H, but without significant trend (confirmed with the Mann–Kendall test). The average dates corresponding to the different locations ranged between 24 May \pm 6 days and 1 June \pm 8 days, with the latest phenology in the plots located at higher elevation. The later phenology was recorded in the years 2013 and 2018, which were the wettest years in the series. The harvest date presented also high variability among years. The average date ranged between 21 and 30 September, with the earliest harvest in mid-September (14 September) and the latest in mid-October (13 October). Despite the high variability, an average advance trend was observed, although it was only significant at two locations (SA and C, confirmed with the Mann–Kendall test). The analysis year by year confirmed later harvest dates in the wet years (such as years 2008, 2013 and 2018), but also in years such as 2016, which was one of the driest years in the series. On the other hand, earlier harvest dates were confirmed in the hot and dry years (such as 2009, 2012 and 2017) as well as in years that suffered both warm and dry conditions (such as year 2015) (Fig. 3).

Variability in grape composition

The average values and range of variation observed in grape composition are shown in Table 2. High variability in grape composition was observed among locations and among years within each location. The highest BW and acidity values were recorded at the highest elevations, while it was opposite for the PVAD. The average BW varied between 199 and 260 g per 100 berries, with the highest values in the S plot, located at 650 m a.s.l., and the lowest in the SA plot, located at 457 m a.s.l. The average PVAD ranged between $10.8 \pm 0.9^\circ$ and $11.6 \pm 1.0^\circ$, with a range within each location of up to 4° . The average titratable acidity varied between 5.1 ± 1.1 and 6.6 ± 1.6 g L⁻¹, which were recorded respectively at the lowest (457 m) and the highest elevation (650 m). Similar results were observed for malic acid, with 1.74 ± 1 and 3.5 ± 0.2 g L⁻¹, respectively for the same locations.

Influence of weather conditions on the vine response

Influence of weather conditions on phenology

As previously mentioned, clear differences were observed in the phenological dates between years with similar response in years

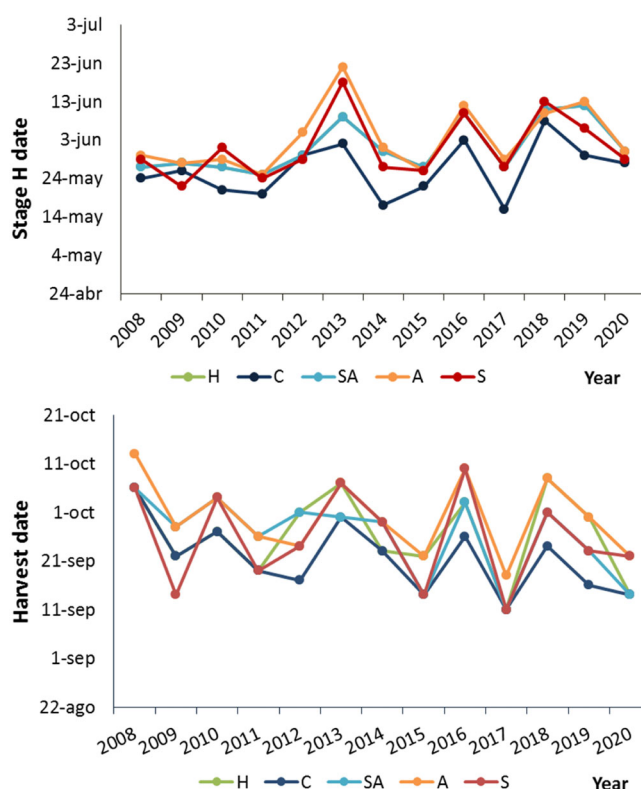


Figure 3. Date at which the stage H (flowers separated) and harvest occurred at the five locations analysed during the period 2008–2020.

with similarities in temperature and/or in precipitation. In order to analyse in more depth the relationship climate–phenology, the response of the vine *versus* temperature and water availability was evaluated. Among all variables related to temperature, the average maximum temperature recorded during the growing season until reaching the corresponding stage was the one that showed better fit (average maximum temperature from the beginning of the growing cycle until reaching stage H and the average temperature for the complete growing cycle). An advance in the date at which stage H was reached when the average Tmax in the previous period increased (Fig. 4a). The change ratio varied between locations, between 1.57 and 3.95 days per 1 °C increase in that period, but the relationship was only significant at two locations. The influence of the available water on the date at which that stage occurred was analysed, considering the index P-ETC, referred to the period from budbreak to reach the stage, and a delay in the dates was confirmed when water availability increased (positive and higher values of P-ETC), at a rate that ranged between 9 and 14 days per each 100 mm of additional available water in that period (Fig. 4c).

For the harvest timing, an advance of the date with the increase in the average TmaxGS could be observed, at a rate that varied between 5.2 and 8.7 days per 1 °C increase in the maximum growing season temperature (Fig. 4b). Regarding the effect of water availability on the harvest date, the analysis showed an advance of the dates when water deficits were of higher magnitude during the whole growing cycle. The relationship, however, was only significant in the plots located at higher altitude, where the change ratio reached values of up to 6.9 days per an increase of 100 mm in the water deficit (Fig. 4d).

Table 2. Average, maximum and minimum values of berry weight (100 berries) (BW-100b), sugar content (expressed as probable volumetric alcoholic degree, PVAD), pH, titratable acidity (AcT) and malic acid (AcM) of Macabeo variety at five locations (H, SA, C, A, S) in Rioja DOCa

Location	Elevation (m)		BW-100b (g)	PVAD (°)	pH	AcT (g L ⁻¹)	AcM (g L ⁻¹)
H	480	Mean	231.0	11.9	3.4	6.1	2.5
		Min-max	192-284	9.7-13.7	3.2-3.6	4.8-8.8	1.2-4.3
SA	457	Mean	199.2	12.1	3.5	5.1	1.7
		Min-max	136-281	10.3-13.6	3.4-3.9	3.4-7.8	0.4-4.1
C	560	Mean	222.5	11.6	3.6	5.3	2.1
		Min-max	149-264	9.5-12.8	3.3-4.0	3.9-8.4	0.6-4.8
A	600	Mean	231.0	10.8	3.4	6.0	2.7
		Min-max	181-284	9.2-12.2	3.2-3.6	3.4-9.2	0.6-5.3
S	650	Mean	260.9	11.1	3.5	6.6	3.2
		Min-max	208-314	10.0-13.1	3.2-3.7	4.8-9.6	0.6-5.8

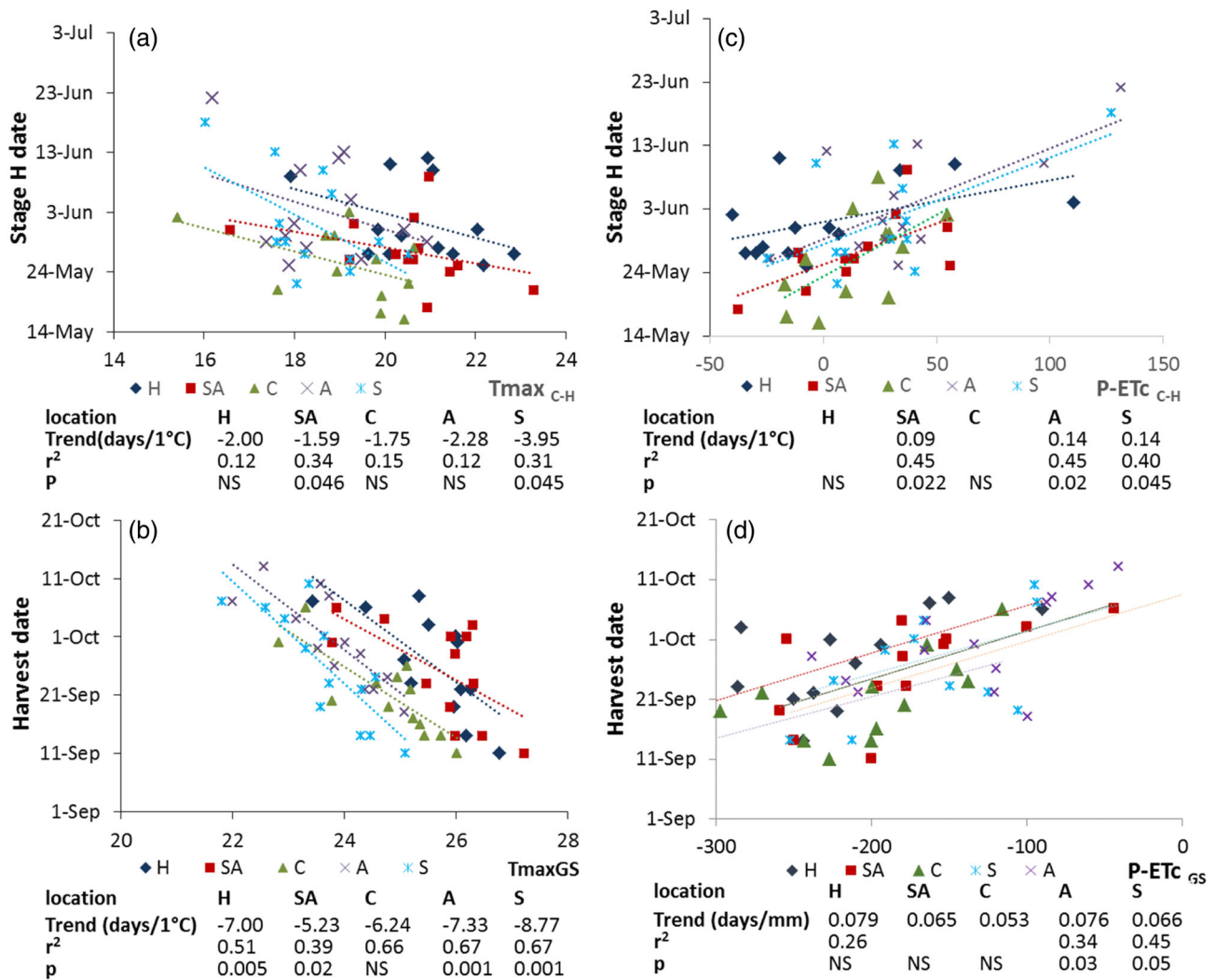


Figure 4. Effect of the average maximum temperature and available water (P-ETc) on the phenological dates, stage H (a,c) and harvest dates (b,d). (C-H: period from the beginning of the cycle to stage H; H-Harv: period between stage H and harvest; GS: growing season).

Influence of weather conditions on grape composition

As sugar content was used in the area to define harvest dates, the differences in this parameter between years were small.

Nevertheless, some differences in the PVAD could be observed among years. PVAD increased with increasing maximum temperatures in three of the five plots, but the influence was only significant

in plot H. In that location Tmax during the period bloom to maturity had a significant positive effect (0.69° per 1 °C increase in the period). Regarding acidity, the recorded values showed that AcT and AcM decreased with increasing maximum temperatures recorded during the growing season (Fig. 5a,c), the change, however, being higher in the plots located at the highest elevation. The average change ratio for AcT ranged between 0.71 and 1.32 g L⁻¹, respectively, for the plot located at lower and higher elevation. The analysed vineyards were non-irrigated, and due to the scarce precipitation during the growing season they suffered water deficits (the average values of the P-ETcGS index ranged between about -150 and -210 mm, with the lowest values at the highest elevation). An increase in acidity (titratable and malic acid) occurred under situations of less water deficit (Fig. 5(b,d)). The average change in acidity with water deficits ranged between 0.7 and 1.3 g L⁻¹ for AcT and between 0.7 and 1.1 g L⁻¹ for AcM, per 100 mm change in the water deficit.

The analysis of the similarity in the response of the vines of the plots analysed obtained in the cluster analysis showed three patterns (Fig. 6). Some points in common appeared year after year, as there was a similarity between plots H and SA (Fig. 6a-c), and a similarity between plots A and S in most of years (Fig. 6a,b).

However, in some years, plot S was isolated (Fig. 6c). Additional variations were observed in relation to plot C, which in some years were linked to plots H and SA (Fig. 6c) and in other years it was linked to plot A (Fig. 6b,c). Plot C was located at intermediate elevation between the other two groups and, in addition, soil characteristics were different. The soils of plot C had lower clay and organic matter content, which imply lower water retention capacity. This fact may contribute to the differences in the response between dry and wet years. Looking at the characteristics of the years in which the different associations appeared, it was found that pattern 'c' occurred in hot and dry years (e.g. 2011, 2012, 2017), while pattern 'a' was found in very wet years (e.g. 2008, 2018) and pattern 'b' in years with intermediate characteristics. The variability in the response of plot C could be attributed to water availability conditioned by soil characteristics. The soils of plot C have lower retention capacity (due to the lower clay and organic matter content) and, although it was at an elevation more similar to that of plots A and S, its response varied between wet and dry years. Under wet and cold years, the vines of plot C could have a response more similar to that on the plot located at higher elevation, while under water restrictions the lower retention capacity may lead to a response more similar to that existing in

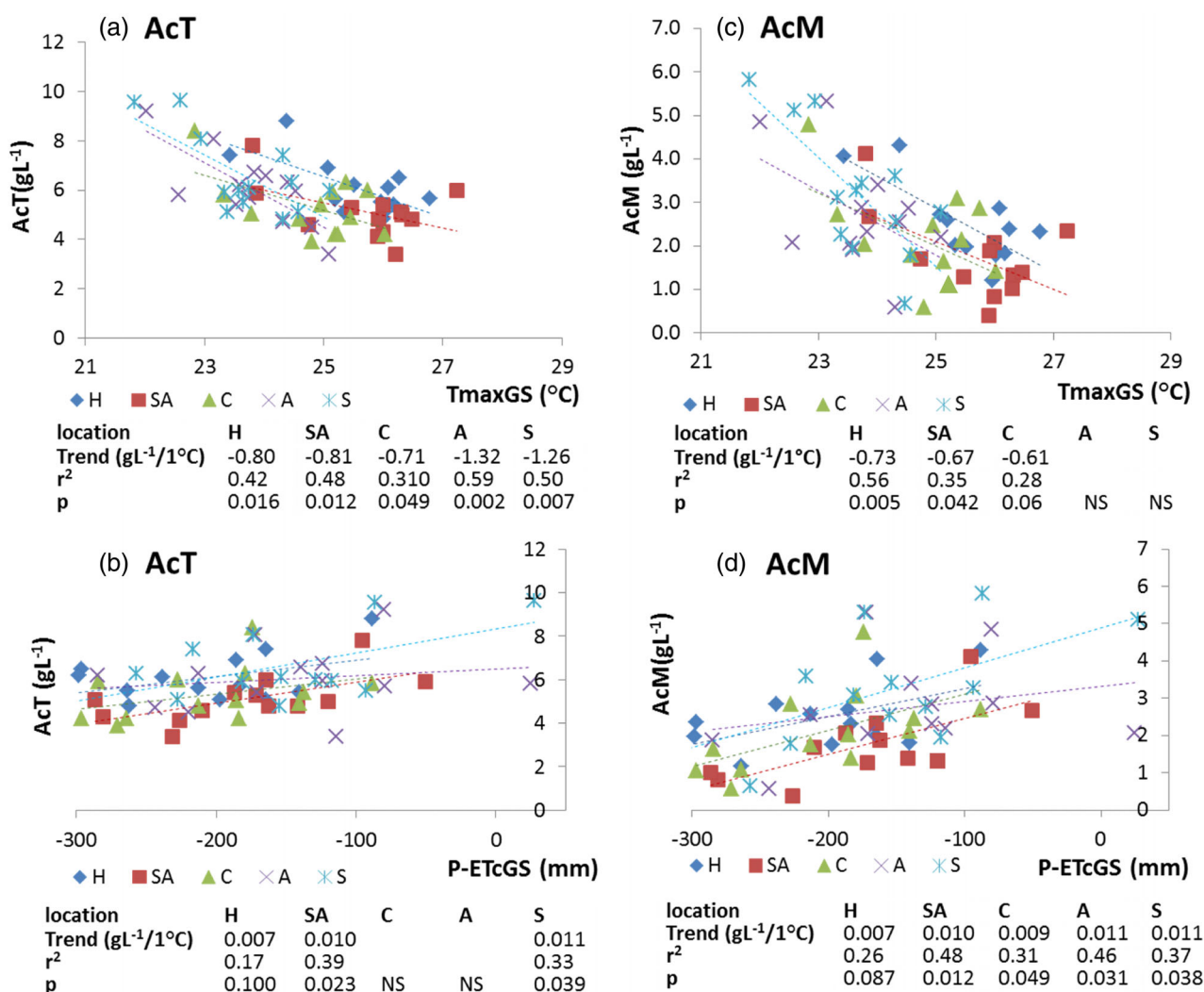


Fig. 5

Figure 5. Effect of the average maximum temperature and available water (P-ETc) on titratable acidity (a,c) and on malic acid (b,d).

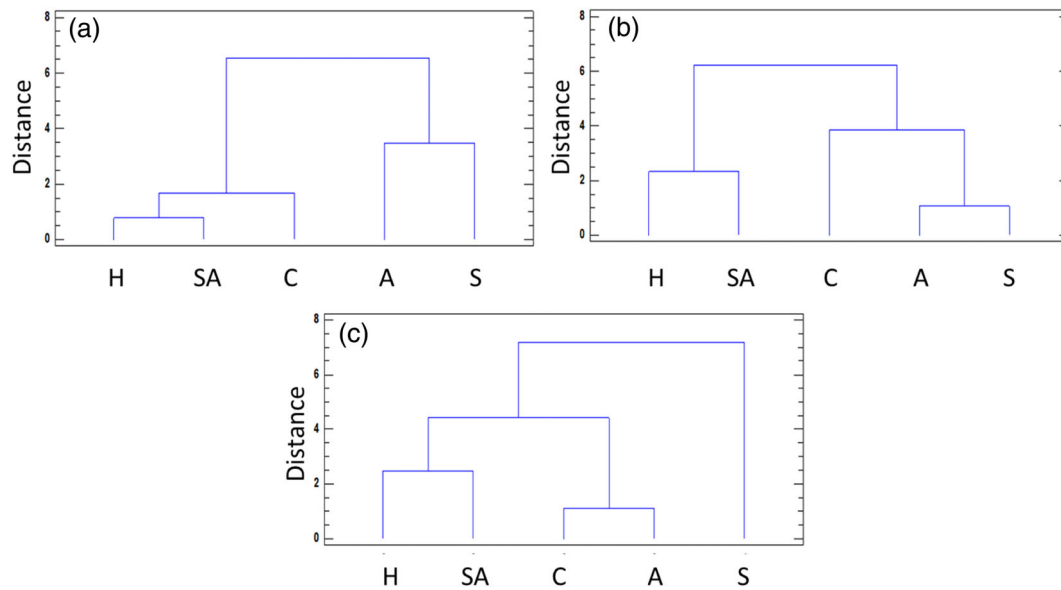


Figure 6. Dendrograms obtained in the hierarchical cluster analysis based on grape composition and harvest, showing the similarity in response of the plots located at different elevations.

the warmest area. In order to evaluate the effect of climate and elevation on the vine response, and given these differences in the soil component of plot C, two groups were considered (plots located at 457–480 (zone LE) and 600–650 m a.s.l. (zone HE), excluding plot C from the analysis. These two groups presented differences in the acidity values, with higher values in the plots located at higher elevation. For these two groups, the effect of climatic variables in different periods during the growing cycle were

considered in the PCA. Three factors were retained in the factor analysis for both zones, which explained 90.0% and 77.2% of the variance, respectively, for LE and HE zones. The results of the factor analysis are presented in Fig. 7. The load matrix after varimax rotation showed some differences between zones, although in both cases the higher loads for AcT and AcM were included in factor F1, which explained 44.3% and 37.2% of the variance, respectively, for both zones. In both zones, temperatures in the ripening period (stage M to harvest), both maximum and minimum, presented the highest loads, with opposite sign to that of acidity. The loads for available water in the same period were higher than in the period between flowering and veraison and with the same sign as that for acidity, but higher in the area located at lower elevation.

DISCUSSION

The great variability in the weather conditions during the period analysed allowed the extraction of information about the vine response under different conditions and the relationship between phenology and grape composition with climate variables. The series of the Macabeo cultivar analysed at several locations of the Rioja DOCa confirmed the effect of temperature and precipitation in phenology, late phenological dates being observed in the coolest and wettest years. In addition, the areas located at different elevations showed average differences in flowering of about 1 week, with later phenology at the highest elevation. The differences could be even higher for later phenological stages and for the harvest date. In the study area, flowering takes place usually at the end of May or the beginning of June, depending on the elevation, while harvest tends to be carried out at the end of September or at the beginning of October. Compared to other areas of Spain, where the variety is also cultivated (Penedès, Costers del Segre and La Mancha, Spain), late phenological timing was observed in Rioja, in particular for harvest. Differences of about 10 days were observed for flowering and even more for harvest between Rioja and Penedès, with later phenological dates in Rioja DOCa.³⁵ The harvest dates are conditioned

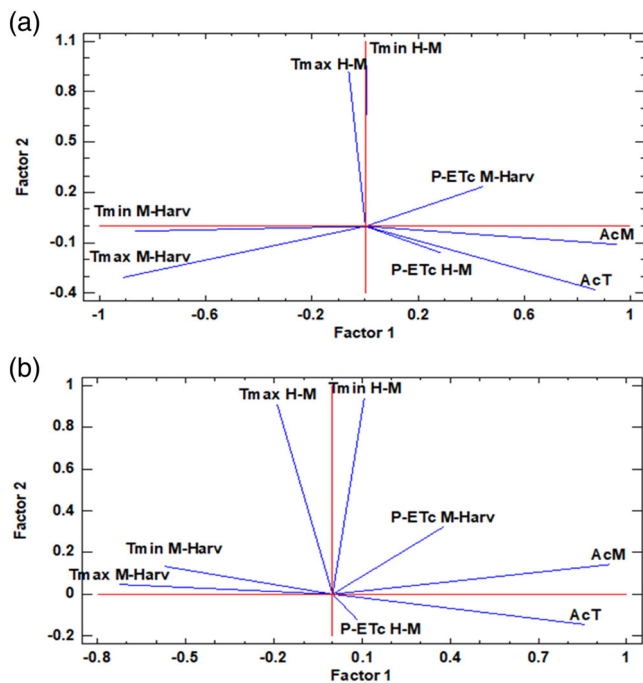


Figure 7. Rotated factor loadings of the analysed variables for the first factor versus the second factor, for (a) areas located between 457 and 480 m a.s.l (LE), and (b) zones located between 600 and 650 m a.s.l. (HE). (H-M, period from stage H to stage M; M-Harv, period between stage M and harvest).

by the final purpose of the grapes and, while in Rioja most grapes of this variety are for wine production, in Penedès most of the Macabeo grapes are dedicated to Cava production, which requires a lower PVAD. Nevertheless, the date at which a given PVAD was reached was always later in Rioja than in the other mentioned viticultural zones. For example, PVAD = 9° was reached, on average, in the Penedès on 28 August,³⁵ while in the analysed areas of Rioja with the earliest phenology PVAD was reached, on average, on 8 September, ranging between 31 August and 23 September. Comparing Rioja with La Mancha, which has a continental climate with cold winters and hot summers, the differences for flowering were smaller (flowering in La Mancha occurred on similar dates (2 June ± 6 days), but there were higher differences for harvest, with earlier dates in La Mancha (3 September ± 5 days) than in Rioja.³⁶ Similarly, in other regions of Spain (Rimat. Coster del Segre DO), where very high temperatures are recorded in summer and Macabeo is used to produce wine, harvest also takes place earlier (5 September ± 8 days; average of 11 years, personal communication) than in the warmest considered area of Rioja. These differences could be associated with differences in temperature and water availability. The differences in temperature between the different zones analysed in this research are comparable to those existing between the lowest analysed area of Rioja and that analysed by Ramos³⁷ in the Penedès, and the differences in phenology were also consistent with those differences in temperature. During the period analysed, the difference in the maximum temperature between the coolest and the hottest year ranged between 3.1 and 3.4 °C, depending on the location. The differences in phenology between those years were, on average, in the two zones of 13 and 23 days for stage H and between 19 and 24 days for harvest. However, in addition to temperature, there were significant differences in precipitation between both years, which could have contributed to that difference. When other years with similar water deficits in the period flowering–harvest and differences in temperature of about 2.5 °C were compared (e.g. 2013 and 2020, with differences in Tmax of 2.7 and 2.5 °C, respectively in both zones), harvest took place between 2 and 7 October in the coolest year and between 14 and 22 September in the warmest year. This means differences of about 15 days for a change of about 2.5 °C. This observed variation in temperature was of the same order of magnitude as the projected increase in the maximum temperature under the RCP4.5 scenario for the time corresponding to the growing season.¹¹ Thus, these values could give an idea of the potential changes in phenology under warmer scenarios, which is in agreement with the projected changes for the same variety in other Spanish areas.³⁷

Grape composition varied significantly from year to year and with an effect of both temperature and precipitation recorded. Regarding sugar content, this variety of late maturation does not reach high levels, with average PVAD values < 12° and much lower at the highest elevations. The impact of temperature on sugar content varied between plots. While in three of the five plots analysed the PVAD increased with increasing temperature, which has been also found by other authors,^{14,38} in other plots the relationship was not significant. On the other hand, although higher PVAD was observed under higher water deficits, the relationship was not significant. This result, however, agrees with those found by Esteban et al.³⁸ in irrigated *versus* non-irrigated vines, which was in most cases higher in irrigated vines.

For acidity, both titratable acidity and malic acid, the variability from year to year was clearly driven by the weather conditions, with the highest values in the wettest and coolest years

(e.g. 2008, 2013 and 2018) and the lowest values in the warmest and driest years (e.g. 2009, 2011, 2012 or 2017). The results are in accordance with that observed in recent decades in other areas and for other varieties,^{14,39–41} which has been associated with an increase in temperature and with differing water stress. In addition, the time at which this increase in temperature occurs may be relevant. In the study case, the ripening period was that in which changes in temperature had the highest influence on acidity, giving rise to a decrease in acidity with increasing temperature (Fig. 6). Sugiura et al.⁴¹ suggested that the temperature recorded in the 40–50 days before harvest date had a great influence on titratable acidity, and they found that for Chardonnay the mean temperature from 60 to 99 days after full flowering had the strongest influence. However, for the analysed variety the effect of temperature seemed to be more relevant during ripening and higher for the warmest area, where the effect of variations in maximum and minimum temperatures could also affect the final acidity values. Volschenk et al.⁴² indicated that malic acid usually increases just before veraison, and Sweetman et al.⁴³ pointed out that heating at veraison and ripening stages reduced malate content. These authors indicated, however, that the regulation of malate metabolism differs between day and night, and if minimum temperatures also increased malate content could be not reduced. These results obtained in the PCA analysis confirmed the negative effect of the maximum and minimum temperature ripening on both titratable acidity and malic acid.

Most of the vines in the study area are managed under rainfed conditions, which means that rainfall is the only water input. The results of the research showed that the vines experienced water deficits between flowering and harvest (between 195 and 270 mm, on average, depending on the plot, with the lowest values at the highest elevation), which conditions the final grape acidity. In the area where precipitation could be scarcer (the area located at lower elevation), available water in the period previous to reach stage M was shown to have the highest influence on acidity compared to the zone located at higher elevation. This result could be due to higher water availability in the area located at higher elevation. Higher water availability in the period before veraison can have a higher impact of the total acid concentration as it is the time at which the synthesis of tartaric and malic acid occurs and when vine vigour and photosynthetic activity are higher during berry growth and up to the onset of veraison. During maturation, high temperatures produce a decrease in titratable acidity and even result in a higher proportion of malic acid. Similar effects have been found for other varieties.⁴⁴ However, in the coolest area, the effect of water availability was less important than that of temperature, and in addition it was the available water during ripening that favours an increase in acidity. In this respect, Chacón et al.²⁹ found that, for Chardonnay, both titratable acidity and malic decreased with increasing water deficits, but when the combined effect of temperature and available water was analysed the effect of water was hidden. Nevertheless, water deficits during ripening were smaller than those recorded before, and smaller in that area located at higher elevation. Water stress, and when it occurs, could affect other grape parameters such as volatile compounds, which seem to change during the ripening period,⁴⁵ and water stress in that period could have more impact for this Macabeo than for other white cultivars.⁴⁶

The differences in the acidity values between the years with extreme situations in relation to the average could give an idea of potential changes under warmer conditions. As mentioned, the lowest acidity values were observed in years such as 2009,

2011, 2012 and 2017 in both zones, but differences in the final acidity in relation to the average values recorded in the series were smaller in the areas located at higher elevation (about 4 versus 5.3 g L⁻¹ and 4.8 versus 6.0 g L⁻¹, respectively, in both areas), while the differences in temperature in the ripening period were of about 1.5 °C. These changes are in line with those pointed out by other authors for other white cultivars. Neumann and Matzarakis⁴⁷ projected a decrease in titratable acidity for the viticultural districts of Baden and Wuerttemberg as well as for the Bodensee area that ranged from 0.5 to 2 g L⁻¹ per 1 °C.

CONCLUSIONS

The period analysed included years with a high range of temperature and precipitation, which allow having information of the phenology and grape composition of the Macabeo cultivar in areas of Rioja DOCa under different climatic conditions and in areas at different elevation. Differences in the phenological dates between the coolest and the warmest years in the series analysed give an idea of the potential changes that warmer conditions could produce, and the potentiality of areas located at higher elevation in this respect. At present, grapes of Macabeo did not attain high sugar contents, and warmer conditions may increase this value in the areas located at the highest elevation. There are also differences in the acidity values between zones, being affected by both temperature and water availability after flowering and, in particular, during ripening. Acidity tends to decrease when the maximum temperature increases and to increase when water deficit decreases, being necessary to combine both variables to extract information for potential changes under climate change. The information could be of interest to winegrowers in the area in order to establish strategies ahead of warmer scenarios.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to disclose.

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