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Characterization of sugar accumulation dynamics in grapes and the factors influencing this process at local scale

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Determining the sugar concentration in grape berries is essential for winegrowers, as it enables them to estimate the alcohol content in the final wine and optimize the harvest date. In the face of climate change and rising temperatures, understanding the factors affecting sugar accumulation dynamics is crucial, to adapt viticultural practices and maintain wine quality. This study aims to analyze the growth and environmental factors involved in sugar accumulation in grapes, using data collected in Saint-Émilion, Pomerol, and their satellite appellations (Bordeaux, France)[1].

Characterization of sugar accumulation dynamics

18 small plots in Merlot vineyards were monitored from 2012 to 2019 (with the exception of 2017, a year marked by a spring frost). Each ripening monitoring plot consisted of 20 vines arranged around a previously installed sensor to measure the local temperature[2]. In addition to temperature, water status and nitrogen nutrition were assessed, close to the harvest date, by carbon isotope discrimination ($\delta^{13}C$)[3] and assimilable nitrogen (Nass) measurements on grape must by enzymatic assay or formalin titration. The phenological stages, and in particular mid-veraison (BBCH 85)[4], were determined by bi-weekly field observations, while berry weight and sugar concentration (measured by the FTIR method, FOSS Analytical, France) were monitored weekly from veraison to a date close to harvest.

The sugar accumulation dynamic at the scale of a berry population follows a sigmoid curve ending in a plateau[5]. In this study, a model was used to characterize the sugar accumulation dynamics in grape berries by plot and year[6]. This model made it possible to estimate the day of the year when sugar concentration reached 95 % of its maximum (Plateau Day) and the sugar concentration (g/L) on reaching 95 % of maximum concentration ([sugar] at Plateau) (Figure 1). The duration in days between observed mid-veraison (Veraison Day) and the modeled day when 95 % of maximum sugar was reached (Plateau Day), was also calculated (Veraison-Plateau Duration) (Figure 1).

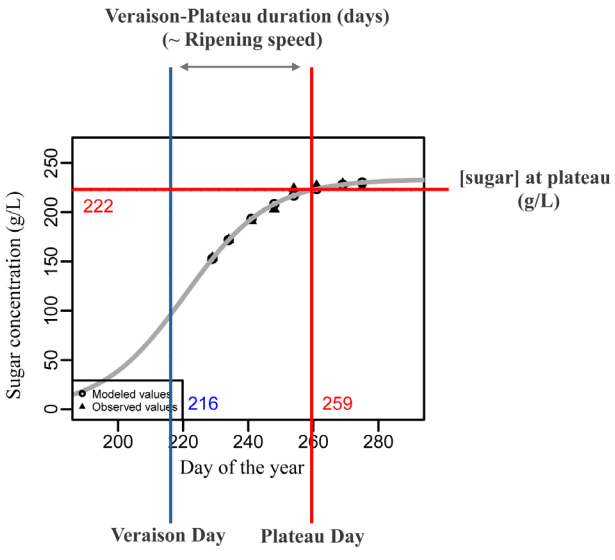


FIGURE 1. Model of sugar accumulation dynamics in grapes from site 1 in 2012 and the adopted ripening indicators. Red lines: estimated parameters; blue lines: measured parameters.

What factors influence sugar accumulation dynamics?

Linear mixed models were used to explore the influence of various abiotic factors (mean temperature (Tmean) between mid-veraison and plateau, $\delta^{13}C$ and Nass) and growth factors (berry weight and earliness of mid-veraison) on sugar accumulation dynamics. Table 1 summarizes the results of these analyses.

TABLE 1. Summary of statistical results for the linear mixed models used to describe berry weight, plateau earliness, plateau sugar concentration and duration of sugar accumulation.

	Tmean Veraison-Plateau (°C)	$\delta^{13}C$ (‰)	Nass (mg/L)	Berry weight (g)	Veraison Day	Veraison-Plateau duration (days)
Berry weight (g)	ns	** Weight ↘ when stress ↗	ns	/	/	/
Plateau earliness	*** Earliness ↗ when Tmean ↗	* Earliness ↗ when stress ↗	ns	ns	** Plateau earliness ↗ when Veraison earliness ↗	/
[Sugar] at plateau (g/L)	** [Sugar] ↗ when Tmean ↗	ns	ns	*** [Sugar] ↘ when weight ↗	ns	*** [Sugar] ↗ when duration ↗
Veraison-Plateau duration (days)	*** Duration ↘ when Tmean ↗	ns	ns	ns	/	/

Nass = assimilable nitrogen in the must, Veraison Day = day when 50 % of berries have reached mid-veraison, $\delta^{13}C$: carbon isotope discrimination, ns = significant, *** = significant at $p < 0.001$, ** = significant at $p < 0.01$, * = significant at $p < 0.05$, / = not considered in the model.

Plateau earliness depends on the mean temperature and the mid-veraison date. A high mean temperature accelerates ripening by bringing forward the appearance of the plateau. A weak water status effect was also observed: the plateau is reached earlier when vines face water deficit.

Sugar concentration at the start of the plateau is mainly influenced by the duration of the accumulation period. Quick ripening is associated with lower sugar concentration at the plateau. A significant berry weight effect was also demonstrated: heavier berries have a lower sugar concentration.

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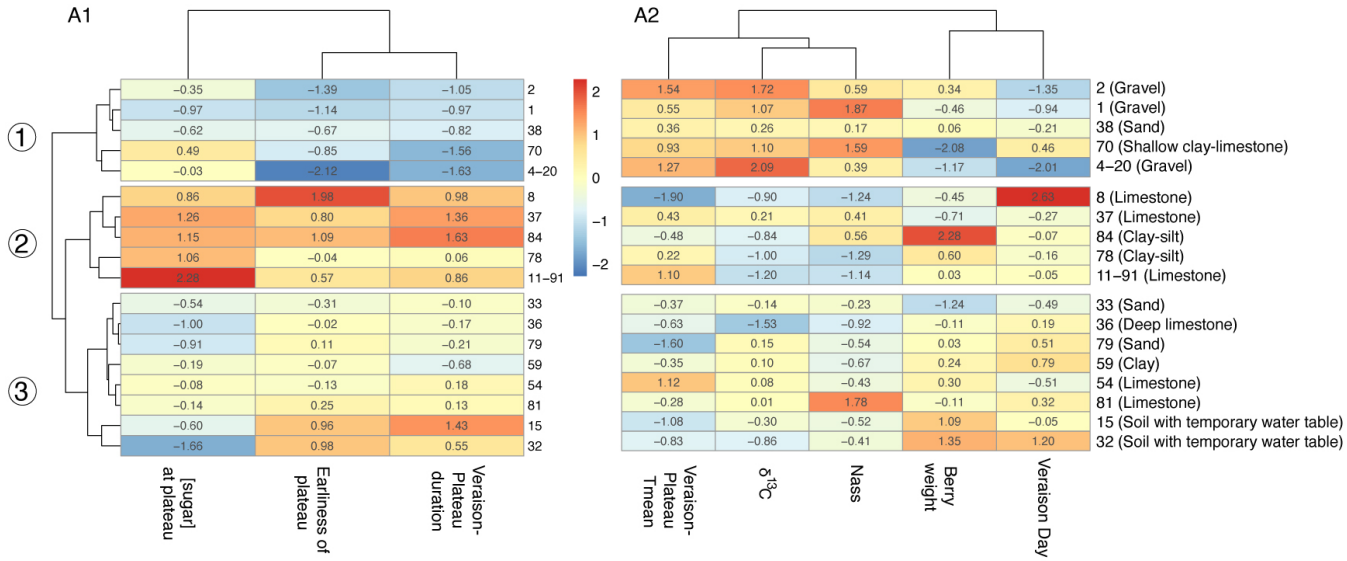


FIGURE 2. A1 - Heatmap with site classification based on ripening variables. A2 - Heatmap with grouping of explanatory variables and classification of sites using the groups of lines from the first heatmap and adding plot soil types.

Lastly, the duration of sugar accumulation is also dependent on the mean temperature: the warmer the weather, the shorter the time between mid-veraison and plateau. However, other factors such as heterogeneous ripening between berries in the same cluster[7] were not taken into account.

Assimilable nitrogen was never identified as a significant variable in this study, and the results are similar with the use of another nitrogen nutrition indicator such as the N-tester (data not shown).

Grouping of plots with similar ripening dynamics across the study area

To identify zones within the study area with homogeneous ripening dynamics, heatmaps were combined with hierarchical clustering to group the plots. Heatmaps provide a visual representation of data matrices using color codes. High values are generally represented by warm colors (red, orange), while low values are represented by cool colors (blue, green). This representation makes it easier to identify trends and variations in the data. Hierarchical clustering, which groups data items according to their similarity, was applied to the heatmaps to reorganize the plots and ripening variables (Figure 2, A1). The explanatory variables (Tmean Veraison-Plateau, $\delta^{13}C$, Nass, Berry Weight and Veraison Day) were added in a second heatmap (Figure 2, A2) and grouped by column. The lines on this second heatmap have been reorganized according to the plot groups identified on the first heatmap (Figure 2, A1), providing a visual representation of the links between plot ripening dynamics and the explanatory variables. Soil types have also been added to complete the link with the terroir.

Three distinct ripening groups have been identified (Figure 2). Group 1 is characterized by a short duration between mid-veraison and plateau, an early plateau, and moderate sugar concentration at the plateau. This group corresponds to plots located to the west of the study area, on predominantly gravelly or sandy soils, subject to water deficits. The temperature during the ripening period is high in these areas, and the plots are characterized by higher concentrations of assimilable nitrogen than for plots in other areas. In this group, quick ripening is associated with a lower final sugar concentration, possibly due to a restriction in photosynthesis linked to a water deficit at the end of ripening, not taken into account by the water supply indicator adopted ($\delta^{13}C$). Group 2 is characterized by slow ripening, a late plateau and high sugar concentration at the plateau. These plots are located on deep loamy clay soils, less prone to water deficit. Lastly, the third group has a low final sugar concentration, and an average plateau and ripening time. It includes plots that are more heterogeneous in terms of terroir, but are characterized by below-average ripening temperatures and Nass levels, with the exception of two plots.

Discussion and application

This study confirms the major impact of temperature during the ripening period on the earliness of the sugar concentration plateau in grapes. It also demonstrates the important effect of ripening duration and berry weight on sugar concentration at the start of the plateau. The analytical method developed in this study is reproducible and could be used by production units such as cooperative cellars or large estates, to group plots according to their ripening dynamics. Grapes from plots with similar dynamics could be vinified in the same tanks or included in the same blends. The explanatory factors for ripening could be extended to include variables not measured in this study, such as yield, plot age, rootstock, clone, or other indicators of mineral nutrition and pre-veraison water status, which are likely to influence ripening dynamics. These results also open up prospects in terms of adapting to climate change, e.g. by using later-ripening grape varieties to delay the onset of ripening, or by promoting viticultural practices aimed at increasing berry weight to limit grape sugar concentration at ripeness. ■

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