Spatial variability of temperature is linked to grape composition variability in the Saint-Emilion winegrowing area

Philippe Pieri[1], Laure de Rességuier[1], Nathalie Ollat[1], Christel Renaud[1], Cécile Thibon[2], Céline Cholet[2], David Lecourieux[1], Sabine Guillaumie[1], Ghislaine Hilbert[1]

[1] EGFV, Univ. Bordeaux, INRAE, Bordeaux Sciences Agro, ISVV, F-33882 Villenave d'Ornon, France
[2] Univ. Bordeaux, INRAE, Bordeaux INP, Bordeaux Sciences Agro, UMR 1366, OENO, ISVV, F-33140 Villenave d'Ornon, France

***Corresponding author:** philippe.pieri@inrae.fr

Keywords: climate change, solar radiation, vineyard, network, anthocyanins, temperature.

Abstract

Elevated temperature during the grape maturation period is a major threat for grape quality and thus wine quality. Therefore, characterizing the grape composition response to temperature at a larger scale would represent a crucial step towards adaptation to climate change. In response to changes in temperature, various physiological mechanisms regulate grape composition. Primary and secondary metabolisms are both involved in this response, with well-known effects, for example on anthocyanins, and lesser known effects, for example on aromas or aroma precursors. At the field scale or at the regional scale, however, numerous environmental or plant-specific factors intervene to make the effects of temperature difficult to distinguish from overall variability. To overcome this, study areas with well-characterized and contrasting temperature conditions were selected. A long-term study of air temperature variability across several Merlot vineyards in the Saint-Emilion, Pomerol and their satellites wine producing areas found significant temperature differences and gradients at various time scales, which were linked to environmental factors. From this study area, a few sites were selected with similar age, soil and training system conditions, and with repeated and contrasting temperature differences during the maturation period. The average temperature difference during the maturation period was about 2°C between cooler and warmer sites, a difference similar to that expected under future climate change scenarios. In close proximity to the temperature sensors at each site, grape berries were sampled three times between green stage and full maturity during the 2019 and 2020 growing seasons. Also, berries from bunches on either side of the row were analyzed separately, allowing an investigation of bunch exposure effect associated with the coupling of berry temperature and solar radiation. Four replicates of pooled berries for each time - site - bunch exposure combination were obtained and analyzed for biochemical composition.

Analyses of variance of the biochemical composition data collected at different sampling times reveal significant effects associated with temperature, site, and bunch azimuth. For instance, anthocyanins in grape skins are clearly influenced by temperature and solar radiation exposure, with up to 30% reduction in warmer conditions.

Introduction

With climate change, the advance of grapevine phenology and increased temperatures in the lower atmosphere will both contribute to a significant rise of temperature directly sensed by the plants and the developing and ripening fruits (Pieri and Lebon, 2014; Fraga al., 2016). Elevated temperature during the grape maturation period is also recognized as a major threat for grape quality and therefore wine quality (Drappier et al., 2019; Neethling et al., 2019; van Leeuwen et al., 2019). Therefore, characterizing the grape composition response to temperature, and especially to higher temperature, at a larger scale during maturation would represent a crucial step towards a sensible adaptation to climate change. In response to changes in temperature, various physiological mechanisms regulate grape composition. Primary and secondary metabolisms in the grape berry are both involved in this response, with well-known effects, for example on anthocyanins and other flavonoids (Tarara et al., 2008; Azuma et al., 2012; Rienth et al., 2014; Pieri et al., 2016; Lecourieux et al., 2017; Lecourieux et al., 2020), and lesser known effects, for example on aromas or aroma precursors (Pons et al., 2017; Wu et al., 2019; Drappier et al., 2019; van Leeuwen et al., 2020). With higher temperature, these effects result mostly in a reduction of quality-related compounds in the berries and are therefore considered detrimental for wine quality. At the field scale or at the regional scale, however, numerous environmental or plant-specific factors intervene to make the effects of temperature difficult to distinguish from overall variability. To overcome this difficulty, study areas with well-characterized and contrasting temperature conditions were selected.

Materials and methods

Based on continuous measurements taken in close proximity to the vine canopies, air temperature variability was assessed across a network of approximately 90 Merlot vineyards in the Saint-Emilion, Pomerol and satellites wine producing area, as part of a long-term study that began in 2012 (de Rességuier et al., 2020). Significant temperature differences and gradients at various time scales were linked to environmental factors, mainly altitude, slope and azimut, latitude/longitude, with the latter accounting for the continentality gradient (Bois et al., 2018; de Rességuier et al., 2020).
From this study area, a few sites were selected with similar age, soil and training system conditions. The selected sites exhibited repeated and contrasting temperature differences during the maturation period, with the network average taken as a reference. The maturation period for each site was estimated by applying two phenology models for véraison and ripening (Parker et al., 2013; Parker et al., 2020) assuming a 220g/L sugar threshold and using inputs of the corresponding measured air temperature series. The average temperature difference during the maturation period was about 2°C between cooler and warmer sites (Table 1), a difference similar to that expected under future climate change scenarios (Pieri and Lebon, 2014; Fraga et al., 2016; IPCC, 2021). There were more differences observed with minimum temperature than maximum temperature (Table 1) and accordingly sites # 6, 16, 23, 74 were labelled “T-“ and sites # 54, 69, 70, 91 were labelled “T+”. It was also observed that this clustering was strongly influenced by geographical and topographical factors: T- sites were localized in the NE hilly plateau, whereas T+ sites were localized at the South (S) margins of the plateau or in the S-facing slopes.

Table 1. Selected Merlot vineyards, including year planted, rootstock, row azimuth, and minimum (Tmin), maximum (Tmax) and mean (Tm) air temperature over 8 years (2012-2019) relative to the network average of ~90 sites during the theoretical véraison-maturity period.

“climate”	# site	year planted	rootstock	row azimuth	ΔT véraison-maturity (°C)		
					Tmin	Tmax	Tm
T-	6	1980	5BB	EW	-1.97	-0.82	-1.39
T-	16	1988	SO4	EW	-1.83	0.03	-0.90
T-	23	1990		NS	-1.34	-0.61	-0.98
T-	74	1985	161-49C	NS	-2.38	-0.56	-1.47
T+	54	1976	41B	NS	1.77	0.47	1.12
T+	69	2000	3309C	NS	0.40	1.74	1.07
T+	70	2003	161-49C	EW	1.31	0.06	0.68
T+	91	2004	161-49C	EW	1.47	0.53	1.00

In close vicinity to the air temperature sensor at each site, usually within the same row and less than 20m away, grape berries were sampled three times (S1 to S3) between green stage and full maturity during the years 2019 and 2020. Also, berries from bunches on either side of the row were analyzed separately. This allowed an investigation of bunch exposure effect associated with the natural coupling of berry temperature and solar radiation associated with row azimut (Spayd et al., 2002; Pieri et al., 2016; Hunter et al., 2020). Four replicates of pooled berries from several different vines and clusters for each time - site - bunch exposure combination were obtained and analyzed for biochemical composition.
It is well known that phenology is strongly influenced by temperature (Parker et al., 2013; Parker et al., 2020) and that higher temperatures may delay véraison and the whole maturation period (Lecourieux et al., 2020). Consequently, a strong bias could potentially affect the comparison of analysis results obtained from samplings at the same time. Therefore, in 2020 it was attempted to minimize this bias by repeating the green stage (S1)

and ~100% veraison stage (S2) simultaneous samplings of both T+ and T-, a few days later for T- sites only (S1b and S2b, respectively), when the same temperature sum above 10°C was reached (with reference to the temperature sum of T+ at the S1 or S2 sampling date, respectively). This rule could not be applied to the ripe stage sampling date (S3) because the viticulturists of T- sites decided to harvest very soon after T+ sites.

Results and discussion

Maturity

Results of biochemical analyses at maturity (sampling date S3, 1-4 days before actual harvest date) revealed relatively little differences between T- and T+ modalities with respect to primary metabolites in grape berry composition. Glucose and fructose concentrations were similar, with slightly less sugars in T+ berries. Tartrate concentrations were nearly identical, whereas malate concentrations were lower in T+, as was expected. These results suggest that the phenology lag between T- and T+ sites apparent at the véraison stage was nearly offset during the maturation period, as far as primary metabolites are concerned.
In contrast, secondary metabolites at maturity were clearly influenced by climate and microclimate factors. Applying an analysis of variance, the variability of anthocyanins concentrations was very significantly linked to the climate (T+ vs. T-), the site, and the bunch exposure (at $p < 0.001$, 0.001 and 0.01 levels, respectively), with non-significant interactions. This influence led to reduced anthocyanins concentrations in grape berries of T+ sites, with clear and consistent differences across sites, combined with a noteworthy influence of bunch azimuth (Figure 1).

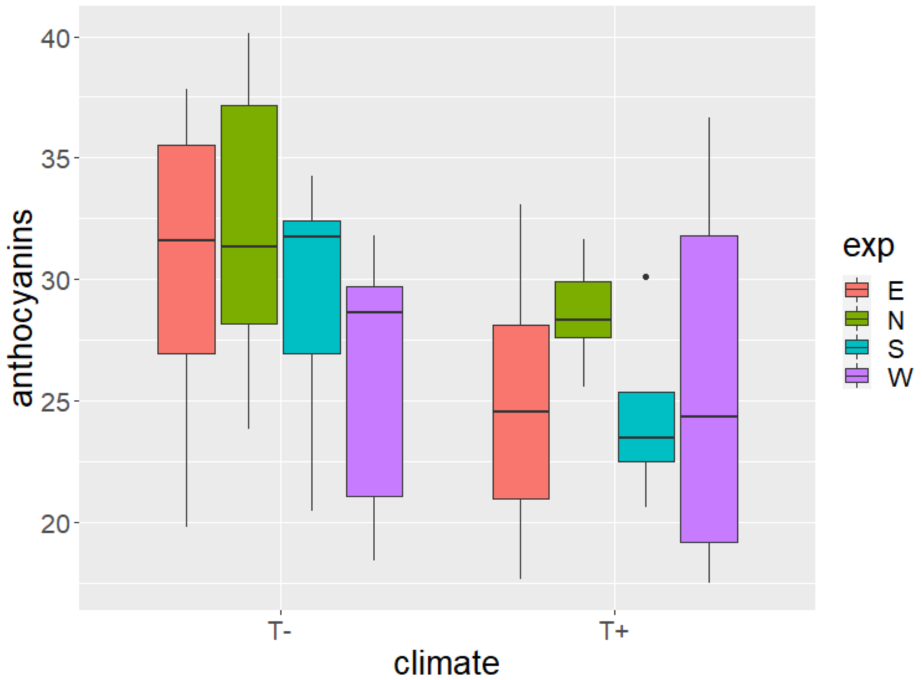

Figure 1. Variations of total anthocyanins concentrations in grape berry skins (µg/mg skin dry weight) at ripe stage (S3) with site climate (T+ vs. T-) and bunch azimuth (exp: north (N), south (S), east (E), west (W)). Boxplots with ordinary settings.

Véraison

Sampling S2 was realized at 100% véraison in T+ sites, and at about 80% véraison in T- sites, with a large variability. The phenology lag was therefore obvious. The S2b sampling was realized 16 days later in T- sites, based on temperature sum above 10°C, and the 100% véraison stage was then reached in all T- sites. At this véraison stage, therefore, biochemical analysis results were investigated by comparing T+ at S2 with T- at S2b. Again at this stage, sugars exhibited very little differences with respect to climate and the other factors. Malate concentrations were also similar, with a trend of lower values in South-exposed bunches, higher values in North-exposed bunches and a large variability in East-exposed bunches of T+ sites. However, tartrate concentrations were strongly influenced by the climate and to a lesser extent by the bunch azimuth, with significantly higher dry-weight tartrate values in T+ sites, and relatively lower values in S-exposed bunches.

Table 2. Analysis of variance results for 2020 measurements of total anthocyanins concentrations in grape berries skins (µg/mg skin dry weight) for S2 (T+) and S2b (T-) sampling dates (with phenology shift between T- and T+ sites minimized).

	df	Sum Sq	Mean Sq	F value	Pr(>F)	Signif.
climate (T-/T+)	1	1237	1237	102.77	2.63e-13	***
site	6	697	116	9.65	7.27e-07	***
exp (bunch azimuth)	2	220	110	9.12	0.000462	***
climate*exp	2	60	30	2.48	0.094730	.
site*exp	4	110	28	2.29	0.074463	.
residuals	46	554	12			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

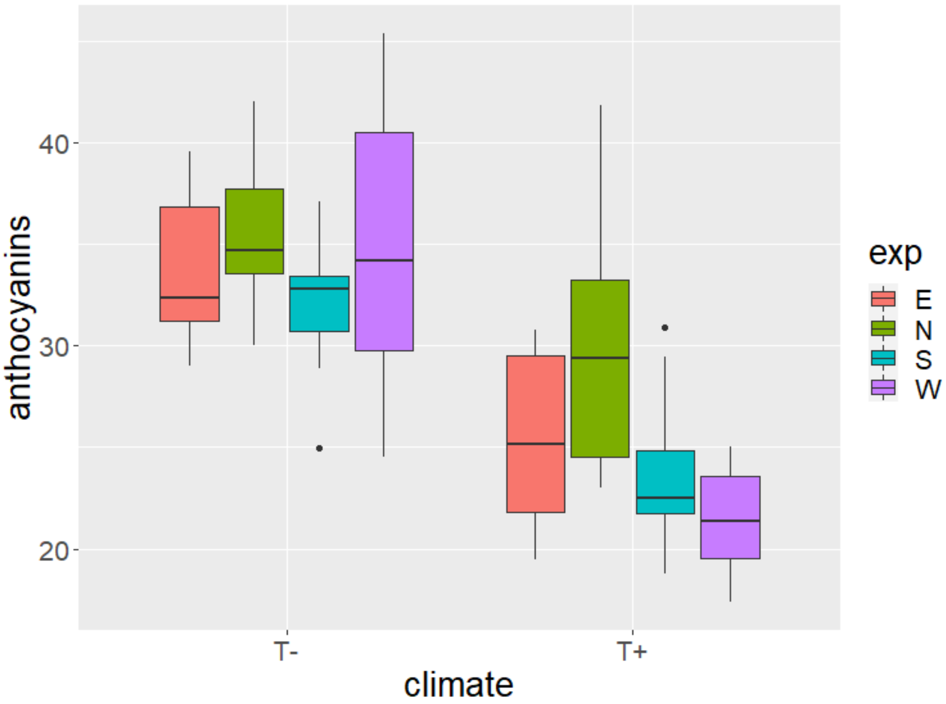

Figure 2. Variations of total anthocyanins concentrations in grape berry skins (µg/mg skin dry weight) at 100% véraison stage (S2 T+ and S2b T-) with site climate (T+ vs. T-) and bunch azimuth (exp: north (N), south (S), east (E), west (W)). Boxplots with ordinary settings.

Analysis of variance applied to total anthocyanins concentrations in grape berry skins (µg/mg skin dry weight), for S2 (T+) and S2b (T-) mixed together, showed strongly significant effects of climate, site and bunch azimuth (Table 2). Interactions were non-significant, although bunch azimuth contributed to interactions with climate and site, which were close to significant.

These significant effects translated into large differences of total anthocyanins concentrations in grape berry skins (Figure 2). Anthocyanins concentrations values at 100% véraison were reduced by ~30% on average in T+ sites, compared with T-. Also, nearly systematic effects of site and bunch azimuth were supported by the results; for example, higher values in North-exposed bunches and lower values in South-exposed bunches were noticeable. One possible interaction could be seen in the case of West-exposed bunches, with a larger reduction in T+, compared to T-, than in the other bunch azimuth categories.

The observed climate and microclimate effects confirm a well-known negative influence of higher temperature on anthocyanins in grape berries. In addition, the variations observed at ripe stage already mostly existed at véraison, suggesting earlier determination. The microclimate effect of bunch azimuth could be explained by solar radiation exposure kinetics since actual berry temperature is naturally coupled to radiation load and differs from air temperature, sometimes to a large extent (Hunter et al., 2020).

Conclusion

These results provide a broad picture of how spatial variability of temperature is linked to grape composition variability in the Saint-Emilion winegrowing area. Simple air temperature measurements taken near the vine canopies over a network in actual producing vineyard conditions allowed an easy selection of consistent, thermally contrasted sites. Variability analysis applied to these thermally contrasted conditions found associated differences in biochemical analysis results at different phenological stages. The sampling approach minimized the potential bias caused by differences in phenology, therefore analysis results at green stage and at 100% véraison could be compared either at the same sampling time, or at the same phenological stage.
Analyses of variance of the biochemical composition data revealed highly significant effects associated with temperature, site, and bunch azimuth, with these effects already mostly established at véraison. Anthocyanins in grape skins were clearly influenced by temperature, with up to 30% reduction in warmer conditions. Solar radiation exposure kinetics and coupled temperature sensed by the berries could explain the microclimate effect of bunch azimuth.

Acknowledgements
The authors thank Mark Gowdy for text reviewing, and CIVB ("Conseil interprofessionnel du vin de Bordeaux" / Bordeaux Wines Council) for funding the study *via* the "Avvenir" project N°51640/180008/9/10.

References
Azuma, A., Yakushiji, H., Koshita, Y., and Kobayashi, S. (2012). Flavonoid biosynthesis-related genes in grape skin are differentially regulated by temperature and light conditions. *Planta* 236, 1067–1080. doi: 10.1007/s00425-012-1650-x

Bois, B., Joly, D., Quénol, H., Pieri, P., Gaudillère, J.-P., Guyon, D., Saur, E., Van Leeuwen, C. (2018). Temperature-based zoning of the Bordeaux wine region. *Oeno One*, 52(4), 291–306. https://doi.org/10.20870/oeno-one.2018.52.4.1580

Drappier, J., Thibon, C., Rabot, A., Geny-Denis, L. (2019). Relationship between wine composition and temperature: Impact on Bordeaux wine typicity in the context of global warming - Review. *Critical Reviews in Food Science and Nutrition*, 59(1), 14–30. https://doi.org/10.1080/10408398.2017.1355776

Fraga, H., de Cortazar-Atauri, I. G., Malheiro, A. C., Santos, J. A. (2016). Modelling climate change impacts on viticultural yield, phenology and stress conditions in Europe. *Global Change Biology*, 22(11), 3774–3788. https://doi.org/10.1111/gcb.13382

Hunter, J. J. K., Tarricone, L., Volschenk, C., Giacalone, C., Melo, M. S., Zorer, R. (2020). Grapevine physiological response to row orientation-induced spatial radiation and microclimate changes. *Oeno One*, 54(2), 411–433. https://doi.org/10.20870/oeno-one.2020.54.2.3100

IPCC. (2021). Climate Change 2021. The Physical Science Basis. (IPCC AR6 WGI).

Lecourieux, F., Kappel, C., Pieri, P., Charon, J., Pillet, J., Hilbert, G., Renaud, C., Gomès, E., Delrot, S., Lecourieux, D. (2017). Dissecting the biochemical and transcriptomic effects of a locally applied heat treatment on developing Cabernet Sauvignon grape berries. *Front. Plant Sci*. 8:53. doi: 10.3389/fpls.2017.00053

Lecourieux, D., Kappel, C., Claverol, S., Pieri, P., Feil, R., Lunn, J. E., Bonneu, M., Wang, L., Gomès, E., Delrot, S., Lecourieux, F. (2020). Proteomic and metabolomic profiling underlines the stage- and time-dependent effects of high temperature on grape berry metabolism. *Journal of integrative plant biology*, 62(8), 1132–1158. https://doi.org/10.1111/jipb.12894

van Leeuwen, C., Destrac-Irvine, A., Dubernet, M., Duchêne, E., Gowdy, M., Marguerit, E., Pieri, P., Parker, A.; de Rességuier, L., Ollat, N. (2019). An update on the impact of climate change in viticulture and potential adaptations. *Agronomy* 9:514. https://doi: 10.3390/agronomy9090514

van Leeuwen, C. van, Barbe, J.-C., Darriet, P., Geffroy, O., Gomès, E., Guillaumie, S., Helwi, P., Laboyrie, J., Lytra, G., Menn, N. L., Marchand, S., Picard, M., Pons, A., Schüttler, A., Thibon, C. (2020). Recent advancements in understanding the terroir effect on aromas in grapes and wines. *Oeno One*, 54(4), 985–1006. https://doi.org/10.20870/oeno-one.2020.54.4.3983

Neethling, E., Barbeau, G., Coulon-Leroy, C., Quénol, H. (2019). Spatial complexity and temporal dynamics in viticulture: A review of climate-driven scales. *Agricultural and Forest Meteorology*, 276–277, 107618. https://doi.org/10.1016/j.agrformet.2019.107618

Parker, A., García de Cortázar-Atauri, I., Chuine, I., Barbeau, G., Bois, B., Boursiquot, J.-M., ... van Leeuwen, C. (2013). Classification of varieties for their timing of flowering and veraison using a modelling approach: a case study for the grapevine species Vitis vinifera L. *Agricultural and Forest Meteorology*. 180, 249–264. https://doi:10.1016/j.agrformet.2013.06.005.

Parker, A. K., de Cortázar-Atauri, I. G., Gény, L., Spring, J. L., Destrac, A., Schultz, H., ... van Leeuwen, C. (2020). Temperature-based grapevine sugar ripeness modelling for a wide range of Vitis vinifera L. cultivars. *Agricultural and Forest Meteorology*, 285, 107902. https://doi.org/10.1016/j.agrformet.2020.107902.

Pieri, P., and Lebon, E. (2014). Modelling the future impacts of climate change on French vineyards. *J. Int. Sci. Vigne Vin*, 33-41.

Pieri, P., Zott, K., Gomès, E., Hilbert, G. (2016). Nested effects of berry half, berry and bunch microclimate on biochemical composition in grape. *Oeno One*, 50(3), 23–33. https://doi.org/10.20870/oeno-one.2016.50.3.52

Pons, A., Allamy, L., Schüttler, A., Rauhut, D., Thibon, C., Darriet, P. (2017). What is the expected impact of climate change on wine aroma compounds and their precursors in grape? *Oeno One*, 51(2), 141–146. https://doi.org/10.20870/oeno-one.2017.51.2.1868

de Rességuier, L., Mary, S., Le Roux, R., Petitjean, T., Quénol, H., van Leeuwen, C. (2020). Temperature variability at local scale in the Bordeaux area. Relations with environmental factors and impact on vine phenology. *Frontiers in Plant Science*, 11, 515. https://doi.org/10.3389/fpls.2020.00515

Rienth, M., Torregrosa, L., Luchaire, N., Chatbanyong, R., Lecourieux, D., Kelly, M. T., Romieu, C. (2014). Day and night heat stress trigger different transcriptomic responses in green and ripening grapevine (Vitis vinifera) fruit. *BMC Plant Biol.* 14:108. https://doi.org/10.1186/1471-2229-14-108

Spayd, S. E., Tarara, J. M., Mee, D. L., Ferguson, J. C. (2002). Separation of Sunlight and Temperature Effects on the Composition of Vitis vinifera cv. Merlot Berries. *American Journal of Enology and Viticulture*, 53(3), 171–182.

Tarara, J. M. M., Lee, J., Spayd, S. E. E., and Scagel, C. F. F. (2008). Berry temperature and solar radiation alter acylation, proportion, and concentration of anthocyanin in merlot grapes. *American Journal of Enology and Viticulture*. 59, 235–247.

Wu, J., Drappier, J., Hilbert, G., Guillaumie, S., Dai, Z., Geny, L., Delrot, S., Darriet, P., Thibon, C., Pieri, P. (2019). The effects of a moderate grape temperature increase on berry secondary metabolites. *Oeno One*, 53(2), 321–333. https://doi.org/10.20870/oeno-one.2019.53.2.2434