IMPACTS OF ENVIRONMENTAL VARIABILITY AND VITICULTURAL PRACTICES ON GRAPEVINE BEHAVIOUR AT TERROIR SCALES

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Abstract

Climate change poses several challenges for the wine-industry in the 21st century. Adaptation of viticultural and winemaking practices are therefore essential to preserve wine quality and typicity. Given the complex interactions between physical, biological and human factors at terroir scales, studies conducted at these fine scales allow to better define the local environment and its influences on grapevine growth and berry ripening. Accordingly, they lead to a greater understanding of the potential future impacts of climate change and adaptation strategies necessary at different spatial and temporal scales. Within the context of climate change, this paper presents the impacts of the local environment and viticultural practices on grapevine behaviour in the mid-Loire Valley winegrowing region, France, namely in the AOP Coteaux du Layon (variety: Chenin) and the AOP Saumur Champigny (variety: Cabernet franc). Both areas were equipped with climatic instruments (weather stations, temperature sensors and rain gauges) and during the growing season, phenological observations and berry composition analyses were effectuated. A strong spatial variability in temperatures and bioclimatic indices was observed within the vineyards. This variability, related to altitude, aspect and nearness to river, was even more evident during extreme events, such as risk of spring frost. Overall, the local climate variability in relation with soil characteristics, notably water holding capacity, was related to grapevine growth and berry composition. Vineyard plots with greater heat accumulation had earlier phenological stages and higher maturity indices. These results illustrate that adaptation solutions to climate change do exist at local scales, in terms of spatial temperature variability, soil properties and viticultural practices, particularly those related to soil management strategies. As adaptation to climate change is essential, these results show that it is necessary to conduct studies at fine terroir scales in order to better understand the spatial variability of local climate and its influences on grapevine behaviour.

Key-words: Spatial variability, climate, soil, viticulture, terroir, local scales, adaptation, climate change

1 INTRODUCTION

Climate change, and particularly temperature increases, have caused impacts on natural and human systems on all continents and across the oceans (Field *et al.,* 2014). In wine growing regions worldwide, significant warming trends have been observed that are associated with changes in the timing of key phenological stages and grape berry compositions at harvest (Jones and Davis, 2000, Duchêne and Schneider, 2005, Tomasi *et al.,* 2011, Neethling *et al.,* 2012). Given that high-quality wines are produced in narrow climatic niches, climate change is one of the major challenges of the 21st century (Keller, 2010). As a response to future climate change, adaptations of viticultural and winemaking practices are therefore essential in order to preserve the quality and typicity of wines produced in various denominations of origin. In this context, several adjustments can be made. For example, changes in cultural practices related to vigour and soil management, use of more drought and heat tolerant plant materiel (Keller, 2010) and more drastically, expansion of viticulture to non-traditional wine growing regions (Hannah *et al*., 2013). However, successful adaptation strategies across different temporal and spatial scales should be constructed on a better understanding of the characteristics of the local environmental and the social behaviour of decision making (Smit and Wandel, 2006). Indeed, given the complex interactions between physical, biological and human factors at terroir scales, studies conducted at these fine scales will allow to better define the local environment and its influences on grapevine growth and berry ripening (Quénol, 2011). Numerous studies have shown that grapevine behaviour is significantly affected by the local environment and viticultural practices (Jackson and Lombard, 1993; Tesic *et al.,* 2002; Van Leeuwen *et al.*, 2004; Barbeau *et al.,* 2006, Carey *et al.,* 2008). Moreover, at local terroir scales, topographical features such as altitude, aspect, etc. influence the spatial climate variability over short distances (Bonnardot *et al.,* 2012; Bonnefoy *et al.,* 2012). Therefore, failure to account for the influence of local environmental factors (climate and soil) and cultural practices on grapevine behaviour and ultimately wine quality, will lead to an overestimation of the future impacts of climate change and less accurate rational adaptation strategies (Adams *et al.,* 1998). Within the context of climate change, this paper aims to present the spatial variability of the local environment, particularly in terms of temperature variables and bioclimatic indices, and along with viticultural practices, to study the impacts of environmental variability on grapevine behaviour at terroir scales.

2 MATERIALS AND METHODS

2.1 Study area and vineyard sites

The study was conducted in the mid-Loire Valley wine growing region, located in the North West of France (Figure 1). At local terroir scales, two experimental sites were selected within the:

(1) AOP Coteaux du Layon, a sweet wine producing area where Chenin blanc is the main variety
(2) AOP Saumur Champigny, a red wine producing area where Cabernet franc is the main variety

The vineyards of both areas benefit from an oceanic temperate climate, with warm summers and mild winters. Yet, in terms of their local climatic conditions (Bonnefoy *et al.*, 2012) and geo-pedological and landscape characteristics, the two sites are greatly contrasted. The wine producing area of Coteaux du Layon is located in the geological formation of the “Massif Armoricain”, composed of eruptive and metamorphic rocks from the Precambrian and Primary Eras. In this area, vineyards are mainly planted on shallow slate soils, containing low to moderate soil water reserves. On the other hand, the wine producing area of Saumur Champigny is located in the geological formation of the “Bassin Parisien”, composed of sedimentary rocks from the Jurassic and Cretaceous periods (Secondary Era) and where vineyards are planted on deep calcareous soils that contain moderate to high soil water reserves. The Coteaux du Layon is also characterised by a more diverse topography, with moderate to steep slopes that follow the course of the Layon River, a tributary of the Loire River. Plains and moderate slopes characterise the vineyards of Saumur Champigny, where the proximity of the Loire River plays an important role on the local climate.

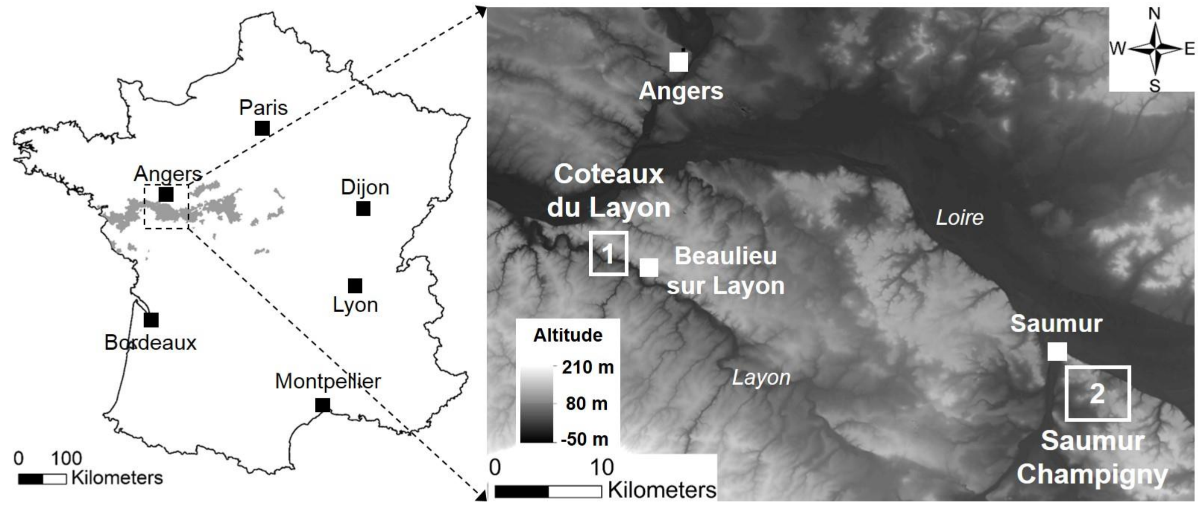

Figure 1: Location of the two experimental sites in the mid-Loire Valley wine growing region, France, namely within (1) AOP Coteaux du Layon and (2) AOP Saumur Champigny.

2.2 Climate data and viticultural measurements

Within each experimental site, a network of complete weather stations, temperature sensors and rain gauges were installed according to the diversity in landscape (terrain relief and aspect, nearness to the river, etc.) and geo-pedological characteristics. Weather stations are located in an open space close to the vineyards, whereas the temperature sensors are installed within the vineyard plots. In total, there are 5 weather stations, 25 temperature sensors and 3 rain gauges in the AOP Coteaux du Layon (Figure 2a) and 7 stations, 35 sensors and 3 rain gauges in the AOP Saumur Champigny (Figure2b). From the climate data obtained in 2013, several climate variables and bioclimatic indices related to grapevine growth and berry ripening were calculated (Table 1). Moreover, to assess the influence of the spatial climate variability on grapevine behaviour, viticultural measurements were carried out on 12 plots of Chenin blanc in the Coteaux du Layon and 12 plots of Cabernet franc in Saumur Champigny. During the growing season, phenological observations were made (flowering, véraison) and during the ripening period (September), berry composition was analysed on a weekly basis as well as a measurement of the isotopic ratio of carbon 12 and 13. The isotope ratio (Δ13C in ‰) permits to assess the level of plant water stress during the period of ripening (Van Leeuwen *et al.*, 2009). The greater the water stress, the higher the proportion of carbon 13 in the berries. The values vary between -20 and -27‰, where -20 indicate a high water stress and -27 an absence of water stress.

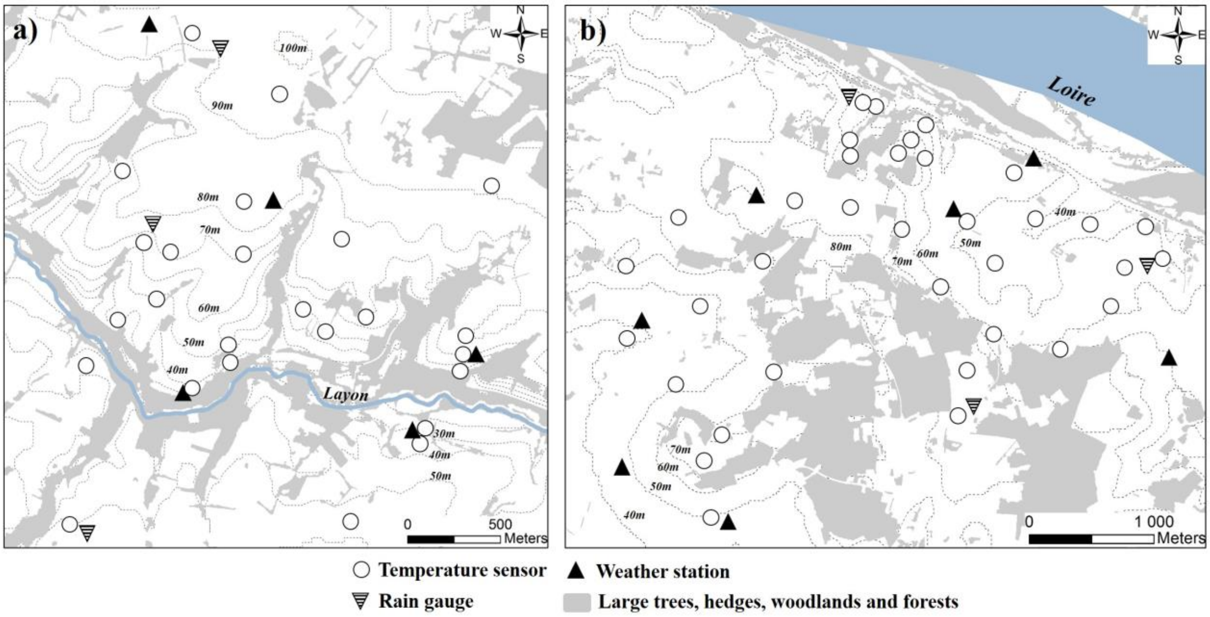

Figure 2: Network of weather stations, temperature sensors and rain gauges installed within the vineyards of the two experimental sites: a) AOP Coteaux du Layon and b) AOP Saumur Champigny.

2.4 Digital topographic and soil data

For this study, a 25m Digital Elevation Model (DEM) was used and, digital soil data (1:10 000) was obtained from the Cellule Terroir Viticole (CTV)[1]. These soil data included the characteristics of naturel terroir units, soil texture, estimated root depth and maximum soil water holding capacity.

3 RESULTS AND DISCUSSION

3.1 Spatial climate variability

Temperature variables and bioclimatic indices calculated using temperature data obtained from sensors, illustrated a strong spatial variability during the 2013 growing season, namely for the period of April to September (Table 1). Mean growing season temperatures varied by 1,1°C in Coteaux du Layon and by 0,9°C in Saumur Champigny. Moreover, mean minimum temperatures varied by 1,7°C and mean maximum temperatures by 1,5°C in Coteaux du Layon, whereas mean minimum temperatures varied by 1,6°C and mean maximum temperatures by 1,1°C in Saumur Champigny. Bonnefoy *et al.* (2012) have shown that this observed spatial variability in seasonal temperatures at local terroir scales can be as significant as the temperature variability at larger scales, such as between two large regions. During temperature extreme events such as risk of spring frost and heat waves, an even greater spatial variability in minimum and maximum temperatures were observed. Minimum temperatures varied by 4,0°C in Coteaux du Layon and by 4,6°C in Saumur Champigny on April 29, while maximum temperatures varied respectively by 2,2°C and by 3,5°C on July 22. In both study areas, the spatial variability in seasonal and daily temperatures was related to the local topography. In Coteaux du Layon, minimum temperatures were principally influenced by altitude, therefore resulting in the lowest minimum temperatures recorded at low elevations, close to the Layon River. Though altitude also affected minimum temperatures in Saumur Champigny, the proximity of the Loire River played an important role in moderating minimum vineyard temperatures. Vineyards situated close to the Loire River recorded warmer minimum temperatures than vineyards located further away, at same altitude levels. The influence of environmental variability on maximum temperatures was much more complex. In general, maximum temperatures were positively correlated with slope steepness in Coteaux du Layon, whereas maximum temperatures in Saumur Champigny were more related to landscape openness, calculated using the IFP index (Jacquet and Morlat, 1997). Consequently the warmest seasonal and daily maximum temperatures were observed in vineyards characterised

[1] Cellule Terroir Viticole: 42 rue Georges Morel, BP 60057, 49071, Beaucouzé, France

by a sheltered landscape (large tress, woodlands, forest, etc.), minimizing airflow and increasing ambient air temperature.

Table 1: Spatial variability in climatic conditions and grapevine behaviour during the 2013 growing season in the AOP Coteaux du Layon (variety: Chenin blanc) and AOP Saumur Champigny (variety: Cabernet franc).

	COTEAUX DU LAYON		SAUMUR CHAMPIGNY	
Climatic variables	**Observed**	**Difference**	**Observed**	**Difference**
Temperature and bioclimatic indices[1]				
Growing season (Apr.-Sept)				
Mean temperature (°C)	16,0 → 17,1	1,1°C	16,4 → 17,2	0,9°C
Growing degree-days (GDD)	1188 → 1340	152°j	1207 → 1355	148°j
Huglin Index (HI)[2]	1795 → 1976	181	1821 → 2005	184
Ripening period (Sept.)				
Daily thermal range (°C, DTR)	12,2 → 16,5	4,3°C	11,9 → 15,2	3,3°C
Cold night Index (°C, CI)[3]	8,7 → 11,4	2,7°C	9,4 → 11,9	2,5°C
Extreme temperature events				
Min temp. (°C, Spring frost)	-1,2 → 2,8	4,0°C	-2,0 → 2,6	4,6°C
Max temp. (°C, Heat wave)	35,5 → 37,7	2,2°C	35,3 → 38,8	3,5°C
Grapevine behaviour				
Phenological stages				
Mid-flowering date (d)	30/06 → 04/07	4d	27/06 → 30/06	3d
Mid-véraison date (d)	29/08 → 04/09	6d	31/08 → 07/09	7d
Ripening period				
Maturity index (26/09/2013)	14,5 → 26,7	12,2	17,4 → 27,1	9,7
Δ13C (12/09/2013)	-20,4 → - 26,7	6,3‰	-22,9 → -26,0	3,1‰

[1]Calculated using data obtained from temperature sensors
[2]Huglin and Schneider, 1998 ; [3]Tonietto and Carbonneau, 2004

2.2 Grapevine behaviour at terroir scales

Agronomic observations illustrated important differences in the timing of phenological stages and in berry compositions during the ripening period (Table 1). In Coteaux du Layon, a difference of 3 days for flowering and 6 days for véraison was recorded, while in Saumur Champigny, the differences were 3 days for flowering and 7 days for véraison. These differences were even more significant during the ripening period, particularly in comparing maturity indices (TSS/TA ratio). Consequently, a strong spatial variability in grapevine behaviour is observed at local terroir scales. For example in Coteaux du Layon, some vineyard plots were in the stage of normal ripening, whereas others already reached the stage of over-ripening, either through the process of "passerillage" (on-vine grape drying) or noble rot (botrytised grapes).

Table 2: Correlation coefficients between total soluble solids (TSS g/L), titratable acidity (TA g/L) and maturity index (MI) on September 26 and indices of precocity for flowering (IPF), véraison (IPV) and cycle (IPCY).

	COTEAUX DU LAYON			SAUMUR CHAMPIGNY		
Index	**TSS**	**TA**	**MI**	**TSS**	**TA**	**MI**
IPF	0,57	**0,80**	**0,81**	0,56	**0,92**	**0,94**
IPV	-0,52	**-0,73**	**-0,73**	**-0,66**	**-0,70**	**-0,66**
IPCY	**0,69**	**0,91**	**0,90**	**0,68**	**0,94**	**0,94**

Values in bold are different from 0 with a significance level $p<0,05$

The influence of the timing of phenological stages on berry composition was evaluated by using indices of precocity for flowering (IPF), véraison (IPV) and the vegetative cycle (IPCY), developed by Barbeau *et al.* (1998). Results from table 2 illustrate that at the two experimental sites, IPV, IPCY and to a lesser extent IPF were significantly correlated with the principal constituents of grape juice, measured on a common date (26/09/2013). Similar to results shown by Barbeau *et al.* (1998) and Tesic *et al.* (2002), these results demonstrate the influence of precocity on grapevine behaviour. Vineyard plots with early phenological stages had greater concentrations in total soluble solids (TSS) and lower levels of titratable acidity (TA), which in consequence was reflected on maturity indices (MI).

2.3 Impacts of environmental variability and viticultural practices

To evaluate the influence of environmental variability and viticultural practices on grapevine behaviour, principal component analysis (PCA) was used. Figure 3 show that 73,80% of total variance is explained in Coteaux du Layon and 75,07% in Saumur Champigny, on factorial plan F1/F2. For both experimental sites, principal component F1 illustrate that total soluble solids (TSS) and maturity indices (MI) were influenced by growing degree days (GDD) calculated from April to September. Vineyard plots with greater heat accumulation were consequently characterized by higher concentrations in sugars and higher maturity indices. Also, titratable acidity (TA) was influenced by minimum temperatures during the ripening period (September), as indicated by the cool night index (CI). Cooler nights during ripening lead to higher concentrations in titratable acidity (TA) whereas warmer night temperatures accelerated the decrease in TA. In Saumur Champigny, TA was also influenced by the daily thermal range (DTR). And finally, results from principal component F2, also show that TSS was partly influenced by the isotopic ratio of carbon 12 and 13 (Δ13C). Therefore, vineyards plots with greater water stress, were associated with higher concentrations in TSS. The level of water stress measured by Δ13C is related to physical factors such as climatic conditions (rainfall, ETP, etc.), soil properties, notably water holding capacity and biological factors (rootstock, grape variety). But also importantly to soil management strategies, such as cover crop and tillage practices in vine inter-row that influence significantly soil water uptake during the growing season (data not shown).

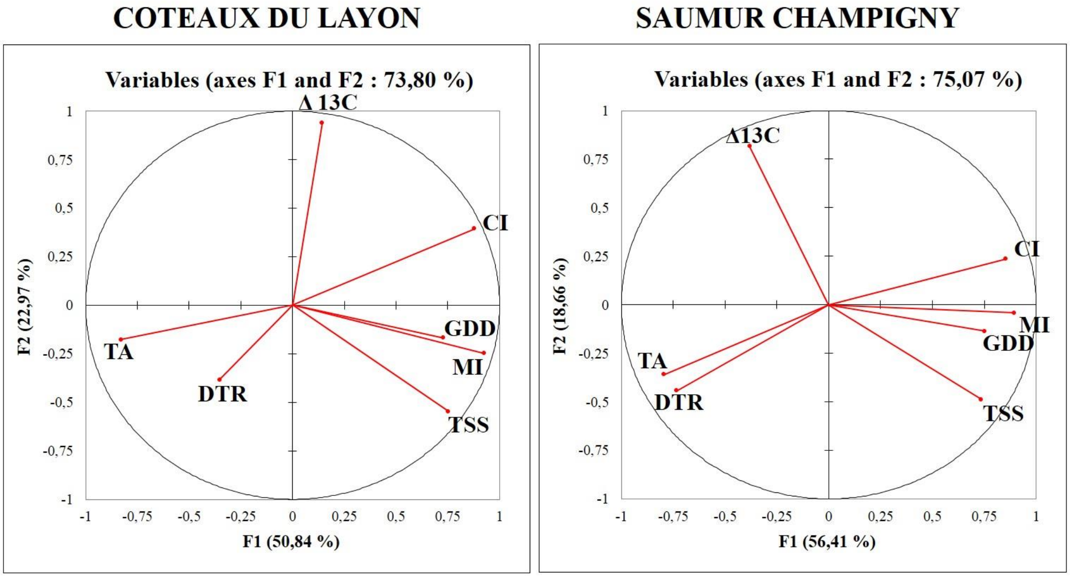

Figure 3: Principal component analysis (PCA) of the influence of environmental variability on grape berry composition, measured on a common date (September 26) in the AOP Coteaux du Layon and AOP Saumur Champigny. (TSS: Total soluble solids; TA: Titratable acidity; MI: Maturity index; GDD: Growing degree days from April to September; CI: Cold night index; DTR: Thermal daily range; Δ13C: Isotopic ratio of C12/C13).

4 CONCLUSION

At local terroir scales, a strong spatial variability in temperature variables and bioclimatic indices was observed within the vineyards of the AOP Coteaux du Layon and AOP Saumur Champigny, during the 2013 growing season. Overall, the local climate variability in relation with soil characteristics, particularly water holding capacity, was related to grapevine growth and berry composition. Vineyard plots with greater heat accumulation had earlier phenological stages and higher maturity indices. These results illustrate that adaptation solutions to climate change do exist at local scales, in terms of spatial temperature variability, soil properties and viticultural practices, particularly those related to soil management strategies. As adaptation to climate change is essential, these results show that it is necessary to conduct studies at fine terroir scales in order to better evaluate the spatial variability of local climate and its influences on grapevine behaviour. Future perspective work is to model the spatial variability in temperature variables, bioclimatic indices and water balances in terms of environmental factors (altitude, aspect, soil properties, etc.). This will allow to better assess heat accumulation and therefore the timing of phenological stages such as flowering, but also to identify the vineyard areas the most sensitive to temperature extremes events such as risk of spring frost and heat waves. These results will enable to better define actual and future agro-climatic potentials, and consequently contributing to the construction of rational adaptation strategies to climate change at different spatio-temporal scales.

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