Viticultural strategies to adapt to climate change: Temporal and spatial changes in land use and crop practices

Etienne NEETHLING[1], Cécile COULON[1], Gérard BARBEAU[1], Vincent COURTIN[2], Cyril BONNEFOY[3], Hervé QUÉNOL[3]
[1]INRA UE1117, UMT Vinitera, 42 rue Georges Morel, 49071 Beaucouzé, France.
[2]Cellule Terroirs Viticoles, UMT Vinitera, 42 rue Georges Morel, 49071 Beaucouzé, France.
[3]Laboratoire COSTEL, UMR6554 LETG du CNRS, Université Rennes 2 – Haute Bretagne, 35043 Rennes, France.
etienne.neethling@angers.inra.fr

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Abstract

Grapevine is a perennial crop, remaining economically productive for more than fifty years. Site selection and perennial crop practices have to be decided before planting. Then, annual crop practices are continuously required to adapt to the weather conditions of each growing season. The economic implications of global warming on viticultural sustainability signify consequently that adaptations of perennial practices should be anticipated. The Loire Valley is a northern latitude French wine region, characterized with a rather short growing season from April to September. The earliness of the grapevine growth cycle and ripening period are essential factors assuring the production of quality wine. They are mainly influenced by the local climate. However, soil properties, such as soil depth, soil temperature and moisture, allow viticultural strategies to adapt to the constrained climate conditions. Simulated future climate scenarios for the Loire Valley illustrate that sites with low water holding capacities may suffer from a greater water constraint, which will reduce yield and influence berry composition. The increase in temperature means also that during warm growing seasons, grapes will reach maturity too early when climate conditions are not optimal for grape ripening. In the Loire Valley, a method has been developed at plot scale to characterize the environmental factors and predict the main variables influencing vine development and berry composition: earliness of the vine cycle, water supply and vine vigor. This method will allow viticultural strategies to adapt to climate change at different temporal scales: modified annual crop practices in the short term, selecting sites with higher water reserves in the medium term and planting new varieties after the mid-century.

1. Introduction

Grapevine is one of the oldest and most important perennial crops in the world. It requires normally a few years to reach reproductive maturity and then remains economically productive for more than fifty years. Before plantation, site selection and perennial crop practices such as the choice of the most adapted grapevine variety and rootstock, planting density and trellising system are very important. Hereafter, these practices are fixed. Annual crop practices are then continuously required to adapt to the weather conditions of each growing season, to assure optimal grape ripening and the production of quality wine (Morlat 2010). Weather conditions, such as the sum of temperatures and water availability to the vine, are significant factors influencing grapevine development, yield, berry composition and consequently the quality of wine (Barbeau *et al.* 2001, Van Leeuwen *et al.* 2009). The Loire Valley, situated in the northwest of France (Figure 1a), is a northern latitude wine region and, in general, is characterized with a rather short growing season from April to September. As a result, the earliness of the grapevine growth cycle and ripening period are essential factors that assure the production of quality wine. Within the same weather conditions, soils with low water reserves will induce an earlier grapevine growth cycle than soils with high water reserves (Morlat 2010). Therefore, soil properties such as soil depth, soil temperature and moisture have allowed viticultural strategies to adapt to the constrained climate conditions. The fourth report of the International Panel on Climate Change (IPCC 2007) indicates that future weather conditions will likely involve higher temperatures, with greater periods of drought and higher annual and seasonal rainfall variability. Consequently, vineyards planted on soils with low water reserves will suffer from severe water stress during these future climate conditions. Vine development and berry maturation are strongly influenced by water stress (Van Leeuwen *et al.* 2009). Moderate water stress is most favorable as it reduces shoot growth and berry size and improves berry ripening without limiting the photosynthetic activity of the vine. However, severe water stress restricts vine photosynthesis and increase leaf and berry temperatures. This will depress the accumulation of sugars, lead to high concentrations in anthocyanins and cause a rapid decrease in the concentration of malic acid. For that reason, the economic implications of global warming on viticultural sustainability signify that adaptations should be anticipated. In this paper, we analyze how weather conditions during the growing season are going to change in the near (2030 to 2050) and far (2080 to 2100) future in the Loire Valley. Furthermore, the berry composition of five vineyard plots, situated on various soil types, is studied during a dry and warm growing season, which is representative of future climate conditions. Finally, a method is presented that permits the characterization of the environmental factors at plot scale. This method will allow viticultural strategies to better adapt to future climate changes at different temporal scales.

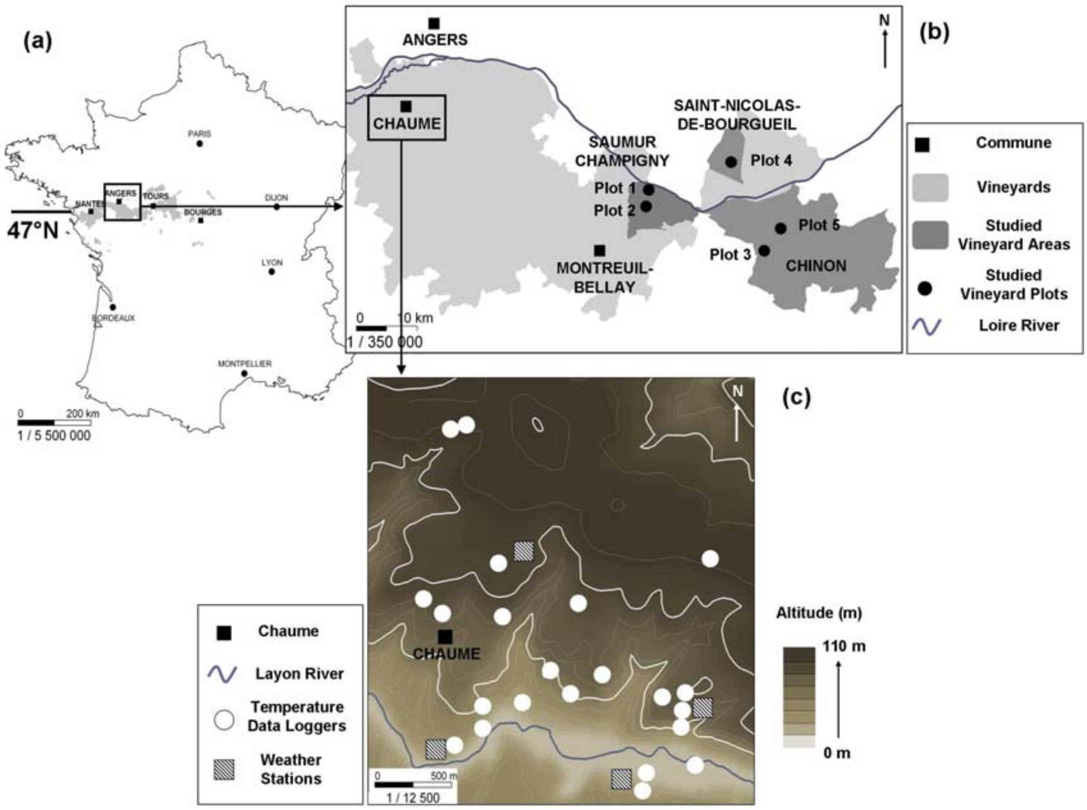

Figure 1: (a) Location of the Loire Valley wine region in the northwest of France. (b) Location of the first study area in the wine producing AOP regions of ‘Saumur Champigny’, ‘Chinon’ and ‘Saint-Nicolas de Bourgueil’. (c) Location of the second study area, situated in proximity to Chaume, a commune in the wine producing AOP region of ‘Coteaux du Layon’ (Source of maps: Geoconcept 5.6).

2. Materials and methods

2.1 Study area

The Loire Valley wine region is situated at the 47°N latitude in the northwest of France (Figure 1a). It is the fourth largest wine region in France, where 14 different red and white grapevine varieties are cultivated in contrasting climates and various soil types. In this paper, we present two study areas, located in the middle Loire Valley. The first is situated in the wine producing AOP regions of "Saumur Champigny", "Chinon" and "Saint-Nicolas de Bourgueil" (Figure 1b). The French AOP "Appellation d'Origine Protégée" body regulates the wine in terms of quality and typicity, where the wine produced should express and have a strong relationship with its unique geographical environment, that is, with its unique "terroir". Five vineyard plots of Cabernet franc were studied, indicated as plot1 to plot5. Cabernet franc is the main red grape variety cultivated in these regions, where quality red wines are produced. The second study area is situated in proximity to Chaume (Figure 1c), a commune within the wine producing AOP region of "Coteaux du Layon". This region is known for the production of sweet white wines, elaborated from the white grape variety, Chenin blanc.

2.2 Meteorological data

Daily temperatures (avg., min., max.) and rainfall data were obtained from 1977 to 2011 from a weather station situated within the vineyards of the Saumur AOP wine region, at Montreuil-Bellay (Figure 1b; altitude 58 m; latitude 47°08'N; longitude 0°08'O; INRA Angers). Moreover, the daily temperatures (mean, min. and max.) and rainfall data were obtained for the same weather station at Montreuil-Bellay, for the period of 2030 to 2050 (near future) and for the period of 2080 to 2100 (far future). These data were simulated with the ARPEGE-Climat model of Météo France (Déqué *et al.* 1994), according to the scenario A1B, which gives an intermediate level of warming by the end of the century (IPCC 2007). The ARPEGE-Climat model permits climate data to be simulated at a resolution of about 50 km in France. Our database, containing the climate observed from 1977 to 2011 and climate simulated for the two periods in the near and far future, was used to calculate several temperature and rainfall indices (Table 1). These indices permitted to characterize each growing season, observed and simulated, taking into account the temperature and rainfall variability between April and September.

Table 1: Temperature and rainfall indices calculated for each growing season from 1977 to 2011 (observed years) and from 2030 to 2050 and from 2080 to 2100 (simulated years).

No.	Code	Description of the temperature indices
1	GST_avg	Average growing season mean temperature (°C, Apr. to Sept.)
2	GST_max	Average growing season maximum temperature (°C, Apr. to Sept.)
3	GST_min	Average growing season minimum temperature (°C, Apr. to Sept.)
4	SPT_avg	Average spring mean temperature (°C, Mar. to May)
5	SMT_avg	Average summer mean temperature (°C, June to Aug.)
6	NDTmax_30	Number of days with maximum temperature ≥ 30°C (Apr. to Sept.)
7	NDTmin_10	Number of days with minimum temperature < 10°C (Apr. to Sept.)
8	WI	Winkler Index ([∑ (Tavg.-10°C)], Apr. to Oct.)
9	HI	Huglin Index ([∑ (Tavg.-10°C) + (Tmax.-10°C)], Apr. to Sept.)
10	DTR	Daily temperature range (°C, Aug. to Sept.)
No.	**Code**	**Description of the rainfall indices**
1	GSR_total	Total growing season rainfall (mm, Apr. to Sept.)
2	SPR_total	Total spring rainfall (mm, Mar. to May)
3	SMR_total	Total summer rainfall (mm, June to Aug.)
4	NDR_1	Number of days with rainfall < 1 mm (Apr. to Sept.)
5	NDR_5	Number of days with rainfall ≥ 5 mm (Apr. to Sept.)
6	NDR_10	Number of days with rainfall ≥ 10 mm (Apr. to Sept.)
7	IRR	Rainfall distribution index (Barbeau 2011, derived from Gini Index)

The climate observed (1977 to 2011) was compared with the climate simulated between 2030 and 2050 and between 2080 and 2100. These two future periods were studied, permitting to understand how weather conditions are going to change in the near future (2030 to 2050) and in the far future (2080 to 2100). An agglomerative hierarchical clustering (AHC) analysis was realized to characterize the observed and simulated weather conditions during the growing season in different climate classes. Finally, the mean values of the different temperature and rainfall indices were calculated for each identified class in the AHC analysis.

2.3 Berry composition data

Five plots of Cabernet franc, grafted on the same rootstock (3309C) were studied for the growing season of 2005. These plots are situated on five different soil types. They were also managed with similar crop practices that permitted a proper comparison between these five plots without the effect of different practices. Several berry composition variables, obtained on 16 September, were measured for each plot (Table 3). They were: sugar concentration in g/L, titratable acidity in g/L, maturity index (sugar/titratable acidity), organic acid ratio in meq/L (tartaric acid/malic acid), anthocyanins concentration in mg/kg and berry weight in g/1000 berries. Given that these plots do not have the same harvest date, a comparable date, namely, 16 September, was chosen to accurately assess the difference in berry composition between the plots. Furthermore, the isotope ratio of $^{13}C/^{12}C$ ($\Delta^{13}C$ in ppm) was also calculated for the five plots on 16 September. The isotope ratio ($\Delta^{13}C$ in ppm) permits to measure the amount of water stress during the period of ripening (Van Leeuwen *et al.* 2009). The greater the water stress, the higher the proportion of ^{13}C is present in the sugars of the berries. The values vary between -20 and -27 ppm, where -20 indicate a high water stress and -27 an absence of water stress. Finally, the ripening speed was also calculated by assessing the maturity index as a function of the Huglin Index, calculated from 1 August (Duteau 1990). The slope of the linear regression represents the ripening speed (Figure 2).

3. Results and discussions

3.1 Future tendencies of growing season weather conditions

The AHC analysis characterized the observed and simulated growing seasons in four types of climate classes. The mean values of the different temperature and rainfall indices were calculated for each class (Table 2). Class 1 is characterized with the lowest mean growing season temperature (16.5°C), the lowest Huglin Index (1773 units) and the least number of days with maximum temperatures exceeding 30°C (9 days). Furthermore, class 1 has the highest total rainfall during the growing season (312 mm) and the most number of days with effective rainfall (20 days).

Table 2: Mean values of the temperature and rainfall indices of each class as identified in the AHC analysis (Data source: INRA Angers).

	Climate Class			
Climate Variable	**1**	**2**	**3**	**4**
GST_avg (°C)	16.5	17.9	18.4	21.0
SMT_avg (°C)	18.8	20.5	21.1	24.4
HI (units)	1773	2083	2184	2744
NDTmax_30 (nr)	9	24	30	65
GSR_total (mm)	312	270	201	140
SMR_total (mm)	139	140	84	49
NDR_1 (nr)	130	141	145	156
NDR_5 (nr)	20	16	13	8

On the other hand, class 4 has the highest mean growing season temperature (21.0°C), the highest Huglin Index (2744 units) and the most number of days with maximum temperatures exceeding 30°C (65 days). Class 4 has also the lowest total rainfall during the growing season (140 mm) and the least number of days with effective rainfall (8 days). From class 1 to 4, the tendency is that growing seasons are warmer with a high amount of days where the maximum temperatures exceed 30°C. At the same time, rainfall during the growing season is lower, with longer periods of drought.

While certain of the simulated years for the near future are identified by the AHC analysis in classes 1 and 2, most (14 of the 21 years from 2030 to 2050) are identified in class 3. Moreover, only the past growing seasons of 1989, 1990, 1995, 1996, 2005, 2006 and 2010 were identified in this class 3. Therefore, the weather conditions observed during these past growing seasons are most likely the type of climate expected for the near future (2030 to 2050) in the Loire Valley. These past growing seasons identified in class 3, such as 2005, permit therefore to better understand the possible vine development and berry ripening expected for the near future in the Loire Valley. During the 2005 growing season, mean growing season temperature was 1°C warmer than the average mean growing season temperature, calculated from 1977 to 2011. Furthermore, the growing season rainfall was 90 mm lower in 2005 than compared to the average season rainfall from 1977 to 2011. This deficit in rainfall was due to a very dry summer in 2005.

However, 16 of the 21 years from 2080 to 2100 (far future) were identified by the AHC analysis in class 4, with none of the observed years between 1977 and 2011 identified in this class. Results illustrate thus that in the far future, weather conditions during the growing season will be significantly different from what have already been observed in the Loire Valley. In the far future, growing seasons will be even warmer and dryer, with no observe growing season comparable with the type of climate expected towards the end of the 21st century.

3.2 Berry composition during the warm and dry growing season of 2005, representative of the near future: Table 3 illustrates the berry composition of the five plots of Cabernet franc on 16 September 2005. The $\Delta^{13}C$ values indicate that plot3 and plot4 suffered from severe water stress, whereas plot5 had no water stress.

Table 3: Berry composition of the five plots of Cabernet franc on 16 September 2005 (Data source: INRA Angers).

	Vineyard Plots				
Berry composition variables	**Plot1**	**Plot2**	**Plot3**	**Plot4**	**Plot5**
Sugar concentration (g/L)	221	217	218	225	213
Potential Alcohol Degree	13.1	12.9	13.0	13.4	12.7
Titratable Acidity (gH2SO4/L)	4,1	4,4	3,6	3,4	4,7
Maturity Index (MI)	53,9	49,5	60,3	66,1	44,9
Ripening speed	0,11	0,11	0,13	0,14	0,09
Tartaric Acid (g/L)	4,3	4,1	4,0	4,2	4,7
Malic Acid (g/L)	1,2	1,7	1,2	1,2	2,1
Organic Acid Ratio (meq/L)	3,6	2,4	3,4	3,5	2,2
Anthocyanins (mg/kg)	2354	1730	2265	2990	2023
Berry weight (g/1000 berries)	1349	1614	1166	1107	1537
$\Delta^{13}C$	-23,3	-25,0	-21,8	-20,1	-26,1

Plot4 is located on the alluviums of the Loire River with a regular distribution of its roots between 0 and 170 cm. However, plot4 has a very low water reserve (80 mm) due to its gravelly sandy texture, which explains the severe water stress observed in 2005. On the other hand, plot5 is characterized with the same soil texture as plot4, but it has a clay horizon at 100 cm, where a significant amount of roots is situated. This clay horizon permits plot5 to have a high water reserve (192 mm), explaining the absence of water stress in 2005. Consequently, the berry composition between these plots is significantly different. Plot4 had the highest concentrations in sugars and anthocyanins, highest potential alcohol degree and the lowest levels in titratable acidity. In contrast, plot5 has the lowest concentrations in sugars and anthocyanins, lowest potential alcohol degree and highest levels in titratable acidity. Figure 2 illustrate furthermore the difference in ripening speed between these plots, where the high water stress in plot4 lead to an earlier and faster berry ripening. A difference in 10 days is observed between the two plots to achieve the same maturity index, namely 40 MI. Finally, the impact of water stress is also seen by the important differences in the berry weights between these two plots. Higher water stress reduces berry size and berry weight, leading to lower yields.

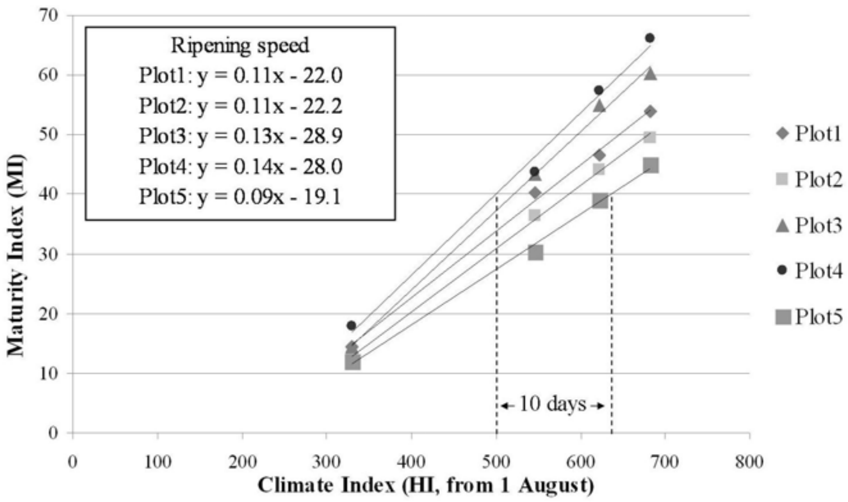

Figure 2: Ripening speed of five Cabernet plots during the 2005 growing season. Ripening speed is represented by the slope, 'a', of the equation y = ax + b (Duteau 1990) (Data source: INRA Angers).

Plots cultivated on soils with low water reserves, will thus suffer from a greater water constraint during warm and dry growing seasons. This will lead to an early and fast grape ripening, where lack of water supply reduces both yield and grape quality. However, an absence in water stress is equally not optimal. An absence in water stress leads to a greater competition between shoot growth and berry ripening, resulting in lower sugar levels. Greater water supply will also increase berry size, leading to a dilution of sugars in a greater berry volume (Van Leeuwen *et al.* 2009). A moderate water stress is therefore most favorable to assure that grapes achieve optimal sugar levels and permit the production of quality wine. Plot1 has a moderate water stress, with high sugar concentrations and common levels in titratable acidity and anthocyanins (Table 3). Plot1 has also a normal ripening speed compared to the other four plots (Figure 2). Plot1 is situated on a medium deep soil (90 cm), with a moderate water reserve (135 mm). However, plot1 has chalk subsoil, where water is available for the vine roots when a large part of the accessible water in the surface layers is depleted, as it occurred in 2005. This soil is therefore less susceptible to water stress given that a large volume of water is stored in the chalk.

In the middle Loire Valley, various studies have illustrated similar results, where the local climate interacts with soil properties, to influence the grape vine development and berry composition. During the warm and very dry growing season of 1990, Morlat et al. (1992) showed for

Cabernet franc plots located on soils, with low water reserves, a blockage in sugar accumulation, very low yields, high anthocyanin concentrations and low levels of acidity. Similarly, during the warm and dry growing seasons of 1995 and 1996, Chenin blanc plots, situated on soils with low water reserves, did not permit the elaboration of natural sweet wines in the 'AOP Coteaux du Layon'. The greater water stress limited the photosynthetic activity of the vine and consequently depressed the sugar accumulation in the berries (Barbeau *et al.* 2001). As a result, these plots with low water reserves were only able to produce dry white wines in 1995 and 1996.

3.3 Method to characterize the environmental factors at plot scale

Given that vine development and berry composition are strongly influenced by the local climate and soil properties, it is essential to study the adaptations that should be anticipated in a changing climate at the scale of the vineyard plot. In this context, a method was developed for the characterization of the environmental factors at plot scale (Morlat 2001). The study of all the environmental factors influencing the development of the vine permits the elaboration of maps that, according to predicted level of vine vigor and earliness of vine cycle, recommend the best varieties adapted to the local environmental conditions as well as the most appropriate rootstocks and crop practices. Moreover, a method for the characterization of spatial variability in weather conditions was developed in 2008 in the frame of the TERVICLIM[1] project. Several temperature data loggers (20) and weather stations (4) were installed within the vineyards of the Coteaux du Layon, in proximity to the commune of Chaume (Figure 1c). In the context of climate change, the aim of this method is to analyze the spatial variability of weather conditions in relation to the local environment, soil properties, grapevine phenology and berry composition. Bonnefoy et al. (2012) illustrated a strong spatial variability in temperature between data loggers situated in low elevations and high elevations. This spatial variability in temperature at plot scale can be of the same importance as the variability in temperature observed between different regions.

Consequently, these methods of the cartography of environmental factors and the study of climate variability permit a better understanding of the spatial variability of soil and weather conditions at the scale of the vineyard plot. It leads to a better prediction of the main variables (earliness of the vine cycle, water supply and vine vigor), which influence the vine development and berry composition. This will allow viticultural strategies to better adapt to future climate changes at different temporal scales. During warm and dry future growing seasons, sites with low water holding capacities will suffer from a greater water constraint, which will reduce yield and significantly influence berry composition. In the short term, annual crop practices will have to be modified on these sites, to better manage the accessible soil water. Lower vigor and lower crop yields would be more favorable as well as the elimination of inter row grasses, that compete with the vines for available soil water. However, in the near future (2030-2050), perennial crop practices should be adapted. Sites with low water reserves would require rootstocks that have longer growing seasons and a higher resistance to water stress. Spatial changes in land use will also be towards sites with higher water reserves or towards sites with northern faced slopes, where temperatures are cooler and the rate of evapotranspiration is lower. This implies therefore the displacement of traditional vineyard sites. Finally, the far future entails weather conditions that have not been observed in the Loire Valley, conditions that would likely be much warmer and dryer. To overcome extreme dry conditions and remain economically sustainable, irrigation would become very important, although legislation forbids the use of irrigation in French AOP wine regions. Lastly, the increase in temperatures means that early ripening varieties will reach maturity too early when climate conditions are

[1] ANR-JC TERVICLIM of CNRS (LETG UMR 6554). Observation and modeling of climate on fine scales in a climate change context.

not optimal for grape ripening. Therefore, late ripening varieties will be more adapted to the warm weather conditions predicted for the end of this century.

4. Conclusion

Although current warmer and dryer weather conditions in the Loire Valley have been favorable for grapevine growing and berry ripening, future climate scenarios illustrate that weather conditions during growing seasons will likely be even warmer and dryer, with the far future (2080 to 2100) illustrating growing conditions that have not been observed in the Loire Valley. During these dry and warm growing seasons, sites with low water holding capacities will suffer from a greater water constraint, which will reduce yield and significantly influence berry composition. In the Loire Valley, a method has been developed at the scale of the vineyard plot to characterize the environmental factors as well as the spatial variability in weather conditions. This method allows the prediction of the main variables influencing vine development and berry composition: earliness of the vine cycle, water supply and vine vigor. Therefore, it will allow viticultural strategies to better adapt to climate change at different temporal scales. In the short term, annual crop practices will have to be modified to control vine vigor and better manage soil water reserves. In the medium term, land use management will signify that new plantations will be orientated towards sites with higher water reserves. In the long term, changes in grapevine varieties and the use of irrigation will be most likely necessary.

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