Volume 51 > Number 2 > 2017

Modified grape composition under climate change conditions requires adaptations in the vineyard

Cornelis van Leeuwen* and Agnès Destrac-Irvine

UMR EGFV, Bordeaux Sciences Agro, INRA, Univ Bordeaux, F-33882 Villenave d'Ornon, France

This article is published in cooperation
with the ClimWine international conference held in Bordeaux 11-13 April 2016.
Guest editor: Nathalie Ollat

Abstract

Aim: Major effects of climate change are an increase in temperature, a modification in rainfall patterns and an increase in incoming radiations, in particular UV-Bs. Grapevines are highly sensitive to climatic conditions. Hence, plant development, grape ripening and grape composition at ripeness are modified by climate change. Some of these changes are already visible and will be amplified over the coming decades; other effects, although not yet measurable, can be predicted by modeling. The objective of this paper is to assess which modifications in wine quality and typicity can be expected and what levers growers can implement to adapt to this changing situation.

Methods and results: This paper focusses on the effect of temperature, vine water status and UV-B radiation in viticulture. Vine phenology is driven by temperature. A significant advance in phenology (i.e. budburst, flowering and veraison dates) has been observed since the early 1980's in most winegrowing regions. The combined effect of advanced phenology and increased temperatures results in warmer conditions during grape ripening. In these conditions, grapes contain more sugar and less organic acids. Composition in secondary metabolites, and in particular aromas and aroma precursors, is dramatically changed. Increased drought, because of lower summer rain and/or because of higher reference evapotranspiration (ET_0), induces earlier shoot growth cessation, reduced berry size, increased content in skin phenolic compounds, lower malic acid concentrations and modified aroma and aroma precursor profiles. Increased UV-B radiation enhances the accumulation of skin phenolics and modifies aroma and aroma precursor profiles. Over the next decades, an amplification of these trends is highly likely. Major adaptations can be reached though modifications in plant material (grapevine varieties, clones and rootstocks), vineyard management techniques (grapevine architecture, canopy management, harvest dates, vineyard floor management, timing of harvest, irrigation) or site selection (altitude, aspect, soil water holding capacity).

Conclusion: Climate change will induce changes in grape composition which will modify wine quality and typicity. However, these modifications can be limited through adaptations in the vineyard.

Significance and impact of the study: This study assesses the impact of major climatic parameters (temperature, water and radiation) on vine physiology and grape ripening. It addresses the issue of how the expected changes under climate change will impact viticulture. It is shown that appropriate levers do exist to allow growers to adapt to this new situation. Among these, modifications in plant material and viticultural techniques are the most promising tools.

Keywords: climate change, adaptation, viticulture, plant material, management systems

Received : 29 August 2016 - Accepted : 21 November 2016
DOI: 10.20870/oeno-one.2016.0.0.1647

*Corresponding author : vanleeuwen@agro-bordeaux.fr

Introduction

The vast majority of the scientific community agrees on the reality of climate change (CC; IPCC, 2014). The major visible effect of CC is an increase in temperatures worldwide. However, important regional differences in temperature increase are observed. This trend will continue and climatologists forecast an increase of 1°C up to 4°C by the end of the XXI[st] century, depending on the rate of greenhouse gas emissions (IPCC, 2014). It is more difficult to predict future rainfall patterns. These will most likely have marked regional and seasonal variability (Moisselin *et al.*, 2002). Extreme effects, like heavy rainfall, are more likely to occur (Zhang *et al.*, 2011). Water deficits experienced by plants and crops will increase even if locally rainfall does not decrease, because of the impact of temperature on reference evapotranspiration (ET_0) (van Leeuwen and Darriet, 2016). Finally, radiation increases with CC, in particular in the UV-B range (Schultz, 2000).

Consequences of climate change on viticulture

A major effect of the increase in temperatures is an advance in the vegetative and reproductive cycles of the grapevine. The subsequent phenological stages (bud break, flowering, veraison, ripeness) are reached earlier (Parker *et al.*, 2011). Hence, grapes ripen in warmer conditions, not only because of the increase in temperatures (direct effect of CC), but also because ripening takes place earlier in the season (indirect effect of CC). Over the last 30 years, a clear modification has been noticed in grape composition at ripeness, as is shown in Figure 1. Grapes contain more sugar and less organic acids, which results in higher pH. Even though it cannot be excluded that other factors act on this trend, like improved viticultural techniques and plant material, it is highly likely that CC participates in this trend. Similar evolutions are reported worldwide (Duchêne and Schneider, 2005). The increase of temperatures also has an impact on aroma compounds (van Leeuwen and Darriet, 2016).

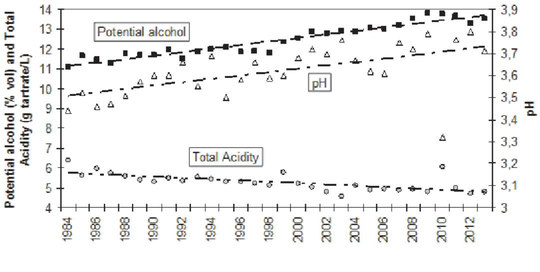

Figure 1 - Potential alcohol levels, Total Acidity and pH of grape juice just prior to harvest in Languedoc from 1984 to 2013 (data: Dubernet laboratory, F-11100 Monteredon-des-Corbières).

The increase of summer drought experienced by grapevines is another effect of CC. In many locations it is more related to an increase in ET_0 rather than to a decrease in rainfall. Hence, climatic water balance becomes more and more negative, as is shown by an example from the Bordeaux area for the period 1952 – 2015 (Figure 2).

Like in any agricultural crop, increased water deficits are likely to impact yield and economic sustainability of wine producing estates. In the last 15 years, a decrease in yield has been observed in most winegrowing regions in France. However, increased water deficit is not the only factor responsible for this trend. In the same period of time the use of herbicides has been much reduced. Hence, grass cover is increasingly present in vineyards, either as a chosen alternative for herbicides, or because of poorer weed control. Grass cover generally has a limited impact on vine water status, because in most vineyard soils vines have access to water reserves in deep layers where grass roots are not developing. However, grass competes with grapevines for nitrogen in the same soil layers, close to the surface, where the organic material is present. It is likely that reduced yields are in many situations as much the result of lower grapevine nitrogen status as of increased water deficits (Pieri *et al.*, 1999; Celette *et al.*, 2009). In any case, if yields are reduced it is important to check whether this is because of reduced vine nitrogen status or because of increased water deficits. While visual symptoms can be confusing (yellow leaves appearing in the fruit zone), grapevine nitrogen and water status should be closely monitored (van Leeuwen *et al.*, 2007; van Leeuwen *et al.*, 2009) before changing management practices to increase yield.

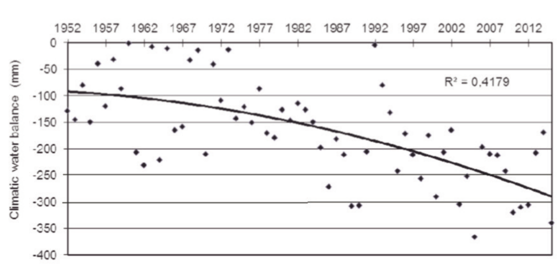

Figure 2 - Evolution of water balance from 1952 to 2015 calculated between April 1 and September 30 for the Saint-Emilion region (France).
Water balance model according to Lebon *et al.* (2003).
Parameters: Soil Water Holding Capacity = 0 mm;
no stomatal regulation.

Increased water deficit generally promotes wine quality, in particular in red wine production, because shoot growth slackening is anticipated and berry size is reduced (van Leeuwen and Seguin, 1994). This promotes fruit ripening and results in the production of berries with less acidity (in particular less malic acid) and increased skin phenolics. The impact of water deficit on berry sugar content depends on its intensity (van Leeuwen *et al.*, 2009). If water deficit is severe, berry sugar content can be decreased because of depressed photosynthesis. If water deficit is mild, berry sugar content will be increased because of reduced competition for sugars between berry ripening and shoot growth. When vines are severely water stressed, wine quality can be impaired. This is particularly true in white wine production (Peyrot des Gachons *et al.*, 2005).

Another aspect of CC is increased incoming radiation, in particular in the UV-B range (Schultz, 2000). This evolution has a positive impact on skin phenolics (Berli *et al.*, 2011; Martinez-Lüsher *et al.*, 2014), but is also likely to modify grape aromas and aroma precursors if too important (van Leeuwen and Darriet, 2016).

Possible adaptations to increased temperatures

For optimum wine quality and terroir expression, grapes should reach ripeness (i.e. optimum composition to be harvested) at the end of the season, when temperatures start to decline (van Leeuwen and Seguin, 2006). Grape ripening under very high temperatures results in unbalanced grapes. They tend to contain high sugar levels, low concentration in organic acids and reduced concentrations in aromas and aroma precursors. Sugar and anthocyanin accumulation are decoupled at high temperatures (Sadras and Moran, 2012). In the Northern Hemisphere, the ideal window for grape ripeness is between September 10 and October 10 (van Leeuwen and Seguin, 2006). When grapes attain ripeness earlier, they might contain excessive sugar levels, resulting in wines with high alcohol content, lacking freshness and aromatic complexity. When grapes are not yet ripen on October 10, they may never reach full ripeness and wines can be green and acidic. In many regions worldwide, the ripening period of the grapes is likely to move out of the ideal ripening window more or less rapidly. Growers will have to adapt by delaying the cycle of the grapevine. In many regions this requires a completely modified approach of viticulture; instead of implementing techniques and choosing plant material to improve *ripeness*, techniques and plant material will have to be modified to *delay* ripeness.

The scope of techniques allowing growers to delay ripeness is very large. Among these, a few have only minor effects and will not dramatically change grape composition and wine style and quality. Others are more invasive and will modify the style of the wine being produced. It should be emphasized that these adaptations are likely to be cumulative. Several adaptations having a small effect, when implemented together can significantly delay vine phenology. Adaptations having little impact on wine typicity can be implemented first and only if these prove to be insufficient, other adaptations with more dramatic effects can be envisaged. Adaptations to delay grape ripening can be sorted out in two categories: modifications in viticultural techniques and modifications in plant material.

An easy adaptation is to advance harvest. This will not allow grapes to ripen in cooler conditions, but it can prevent an imbalance of sugar to acid ratio in grape must and excessive pH. It is a matter of observation that growers are for the moment being *delaying* harvest (i.e. increasing the number of days between veraison and harvest) rather than *anticipating* harvest (Figure 3). Alcohol content and pH in wine do increase because of higher temperatures, but also because of modified harvest decisions.

Several viticultural techniques allow delaying phenology. Late pruning (in February or March in the Northern Hemisphere) will delay bud break by a few days (Friend and Trought, 2007). However, for practical reasons it is not possible to prune all the vineyards of an estate just prior to bud break, because of workforce management issues.

In some areas, where historically full maturity was difficult to obtain (typically Cabernet-Sauvignon in

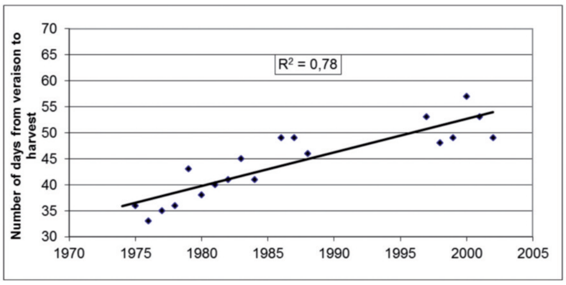

Figure 3 - Number of days from veraison to harvest for a block of Cabernet-Sauvignon in the appellation Margaux, from 1975 to 2002 (data ISVV, Guy Guimberteau and Laurence Gény).

the Médoc), grapes are trained with short trunks. This was done to increase exposure of grapes to high temperatures, because during the day, maximum temperatures are higher close to the soil surface. An increase in trunk height will expose grapes to slightly reduced temperatures (Reynolds and Vanden Heuvel, 2009). If leaf area to fruit weight ratio is meant to remain equal, the height of row hedging should be increased by as much as the trunk height.

A reduction in leaf area to fruit weight ratio can delay veraison (Parker *et al.*, 2014). However, it has many other implications. Some of them are interesting, like a decrease in grape sugar without much impacting grape acidity (Parker *et al.*, 2015). However, others might be detrimental to wine quality, like a possible reduction in grape phenolic compounds (Kliewer and Dokoozlian, 2005) or an increase in herbaceous aromas in grapes and wines. These aspects of modified leaf area to fruit weight ratio require further investigations.

The choice of plant material is certainly the adaptation with the greatest potential of modifying the reproductive cycle of the grapevine. The genetic variability within cultivated grapevine varieties has been explored through clonal selection. In the viticultural context of the XXth century, the selection of early ripening and high sugar producing clones may have made sense (Schöffling and Deroo, 1991). But today, new clones have to be selected based on opposite criteria. In this context, it is of utmost importance to maintain genetic diversity among cultivated grapevines, because clonal selection is a never ending story (van Leeuwen and Roby, 2013). New clones will always have to be selected to adapt to a changing environment and changing production targets.

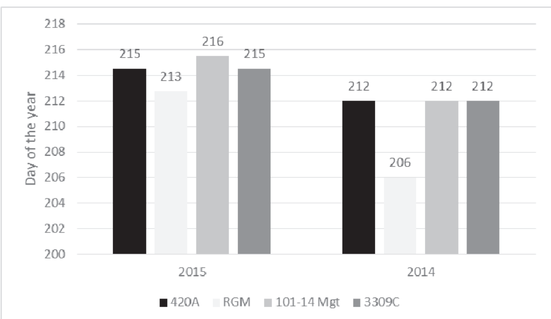

Figure 4 – Day of the year for 50% veraison for Merlot grafted on 4 different rootstocks in the Saint-Émilion area (Bordeaux, France) in 2014. Boehler and van Leeuwen, unpublished results.

Rootstocks can have an impact on phenology. Late ripening rootstocks can delay phenology by as much as 2-6 days depending on the vintage, compared to early ripening rootstocks like *Vitis riparia* cv Gloire de Montpellier also called RGM (Figure 4).

The choice of the grapevine variety has a very big impact of the timing of grape ripening. When a wide range of varieties are cultivated in a single vineyard block, the time span of ripeness between the most early and the latest ripening variety is over 60 days. In regions where traditionally several varieties are cultivated, it is possible to increase the proportion of late ripening varieties. In Bordeaux, Cabernet-Sauvignon, which ripens 2 weeks later than Merlot, only accounts for 20% of the planted area. Hence, there is a huge potential for delaying ripeness by progressively replacing Merlot (today 58% of the planted area) by Cabernet-Sauvignon. In the Languedoc area, Mourvèdre, one of the latest ripening varieties of the *Vitis vinifera* species, can replace the early ripening Syrah, or Grenache, which is handicapped by excessively high sugar concentrations in grapes at ripeness. When these changes *inside* the traditional variety mix of winegrowing regions turn out to be insufficient to maintain ripeness after September 10, it might become necessary to import non-local grapevine varieties. However, these will have to be tested for their aptitude to produce wines close to the typicity of the wines currently produced. This is the objective of the VitAdapt project at the *Institut des Sciences de la Vigne et du Vin* in Bordeaux, where 52 varieties are currently tested for their aptitude to one day replace the actual Bordeaux varieties. Results from this

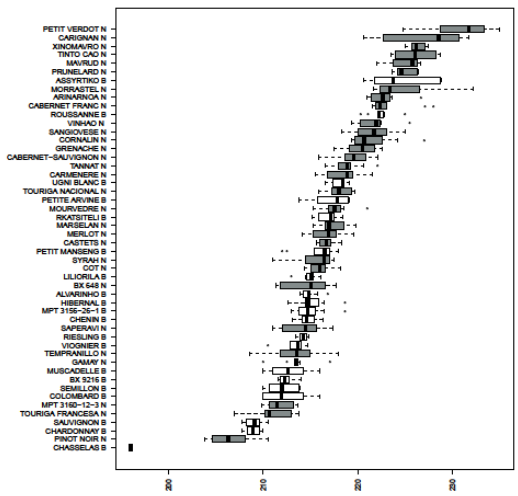

Figure 5 - 50% veraison dates for 52 cultivars in the VitAdapt experiment in 2014 (day of the year). Data are averages of 4 replicates.

project show the huge variability in precocity among cultivars of the *Vitis vinifera* species. 50% veraison dates can vary by as much as 25 days between an early variety (Chasselas) and a late variety (Petit Verdot, Figure 5).

Some of the above mentioned adaptations will induce little or no changes in wine style and quality: increase in trunk height, late pruning, selection of later ripening clones, the use of later ripening root-stocks and the increase of late ripening varieties in the local variety mix. Even if, when taken separately, each of these adaptations only delay grape ripening by a few days, their cumulative effect might reach more or less three weeks. Modeling of the advance in grape ripening shows that this might be sufficient up to 2050 (Brisson and Levrault, 2010). In the second part of the XXIst century, more invasive adaptations, like severe reductions in leaf area to fruit weight ratio, or the introduction of non-local, later ripening varieties will, most likely, be unavoidable.

Possible adaptations to increased drought

In wine production, confusion among the symptoms of nitrogen deficiency and water deficit is rather common. Both limiting factors provoke yellowing of basal leaves and yield reductions. Hence, before implementing any adaptation to increased drought, it is recommended to assess vine water status, e.g. by measuring stem water potential or $\delta^{13}C$ in grape sugar at ripeness (van Leeuwen *et al.*, 2009) and vine nitrogen status, e.g. by means of petiole analysis or assessment of Yeast Available Nitrogen in grape must at harvest (van Leeuwen *et al.*, 2007).

The choice of adequate plant material is without any doubt the most powerful tool to adapt wine production to increased drought. Rootstocks are highly variable in their adaptation to dry conditions. 110R and 140 Ru are reputed highly resistant; 110R has the advantage of promoting at the same time grape quality potential (Ollat *et al.*, 2015). The GreffAdapt project has been set up at the *Institut des Sciences de la Vigne et du Vin* in Bordeaux to compare French and non-French rootstocks in their resistance to water deficits. It should be a priority of breeding programs to create even more drought resistant root-stocks than those actually cultivated. The underlying genetic mechanisms for drought resistance in root-stocks have recently started to be investigated (Marguerit *et al.*, 2012).

Differences in drought resistance among grapevine varieties have also been reported (Schultz, 2003). Mediterranean varieties are generally well adapted to drought. Among Atlantic varieties, Cabernet-Sauvignon is more drought resistant than Merlot. Drought resistance among *Vitis vinifera* varieties needs further investigation. A clear classification of these varieties with regard to drought tolerance would be a welcome contribution to the scientific literature.

Another option for adapting the cultivation of the vine to increased drought involves the training system. In Mediterranean region, growers have developed over the centuries a training system that is particularly resistant to drought: the Mediterranean bush vine, or gobelet (Santesteban *et al.*, 2016). This training system also shows very high quality performance, in particular in Chateauneuf-du-Pape (France) and Priorat (Spain). Gobelet vines have moderately low leaf area on a per hectare basis, which reduces vine transpiration. Because yields are also moderately low, leaf area to fruit weight ratio is not altered. Moreover, this training system has low production costs because there is no trellising system to be set up and maintained and no shoot positioning and pruning wood removal to be carried out. Hence, despite moderately low yields, the production cost per kg of grapes is not necessarily high (Roby *et al.*, 2008). Unfortunately, in a time of increasing drought frequency this drought resistant training system is being abandoned because no harvesting machines are currently adapted to harvesting gobelet trained vines. The development of such a harvester should be a priority for the research community working on vineyard mechanization.

Vine water status depends as much on climatic parameters (rainfall, ET_0) as on soil water holding capacity (SWHC). When SWHC is high and winter rainfall sufficient to replenish the soil's reservoir, vines can face long periods of drought without experiencing detrimental effects of water stress. In a period of increased frequency and intensity of water deficit, vineyard soils should be selected on their SWHC to compensate for climatic drought. SWHC can easily be calculated from a soil pit study when knowing soil texture, percentage of stones and potential rooting depth.

Vines resist better to water deficit stress when yields are low. This is because water deficit impacts photosynthesis. When photosynthesis is reduced, the vine can only bring to full ripeness a limited amount of grapes. In soils with low SWHC, negative impact of water deficit stress on grape quality can be avoided by yield reductions (green harvest). This is of course only an option in vineyards with high added value.

Irrigation can also allow avoiding detrimental effects of water deficit stress, in particular on grape yields (Tomás *et al.*, 2012). However, among other options to adapt viticulture to water deficits, irrigation must be considered as the last possible option, because it also has a certain number of drawbacks. Irrigation has a high financial and environmental impact. The cost of implementing irrigation, including amortization of the irrigation system, the price of the water and the monitoring of vine water status, is approximately 500€/ha (Nicolas Cellié, personal communication). This cost is generally compensated by an increase in yield. The cost of the infrastructures to bring the water to the vineyard blocks is not included in this calculation. However, although it is generally paid for by the community, the price can be very high. In irrigated areas, the paradox is that lower located blocks (closer to the river) generally have access to water (although they do not necessarily require irrigation), while blocks located in more remote and mountainous areas do not. This might compromise viticulture in mountainous regions with a high quality potential, just because they can no longer compete with irrigated areas located on the valley floor.

Another aspect of vineyard irrigation is the question whether, in a period of rarifying water resources, the irrigation of a crop, which is naturally highly resistant to drought, should be a priority compared to utilization for drinking water or food-crops. Many regions where vineyards have been irrigated for decades (California, Australia) are confronted to issues related to the use of this limited resource (Hannah *et al.*, 2013).

Finally, irrigation can lead to salt built-up in soils, making the soil eventually improper for vine cultivation (Walker *et al.*, 2010). This is a process which takes several decades and depends on the amount of winter rain. Only regions with low winter rainfall are subject to this process. Some regions in Argentina and Australia are already facing serious issues with salt stress. For this reason, vines should be cultivated without irrigation whenever possible.

However, when viticulture is not economically sustainable without irrigation, despite the implementation of all other possible adaptations, the amount of irrigation water applied should be as low as possible. This so-called deficit irrigation (Medrano *et al.*, 2015) is possible when vine water status is closely monitored, e.g. through water potential measurement (van Leeuwen *et al.*, 2009), sap flow measurements (Mercier *et al.*, 2012) or surface renewal (Shapland *et al.*, 2012). The efficiency of irrigation can be assessed at the end of the season through $\delta^{13}C$ measurement on grape sugar (van Leeuwen *et al.*, 2009).

Possible adaptations to increased radiation

Exposure of grape bunches to direct radiation increases the concentration in skin phenolics and also modifies the relative abundance of grape aromas and aroma precursors (Darriet *et al.*, 2016). Particularly, an increase in the level of ripeness can lead to higher concentrations of volatile compounds associated in wines with cooked fruit aromas (Allamy, 2015). The increase of skin phenolics enhances grape quality potential for red wine production, but is considered as a drawback in the production of white wines. High levels of radiation before veraison can cause sunburn damage on grapes (Smart, 1987). This can impair grape quality potential for both red and white varieties. To avoid sunburn damage, canopy management should favor the presence of one leaf layer in front of the grape bunches. Leaf pulling has to be avoided or limited to a strict minimum. If this solution is not efficient enough, special screens filtering UV-B can be set up in the bunch zone (Schultz *et al.*, 1998).

Conclusions

Climate change induces increased temperatures, drought and incoming radiation, in particular UV-B radiation. These changes have major effects on grape growing and wine production. However, a whole range of possible adaptions allow growers to continue to produce high quality wines at economically sustainable yields in a changing climate. Among these, modifications in plant material should be considered as a priority, because they are environmentally friendly and they do not increase production costs. Later ripening varieties and clones can be the answer to higher temperatures and drought resistant varieties and rootstocks to increased water deficits. Most of these adaptations, which are studied in the framework of the INRA metaprogram LACCAVE (Long term impacts and Adaptations to Climate ChAnge in Viticulture and Enology, Ollat and Touzard, 2014), most likely have a cumulative effect. This will allow to first implement those that have a limited impact on wine quality and style. More profound changes, like the introduction of non-local, later ripening grapevine varieties might become necessary in the second half of the XXIst century.

References

Allamy L., 2015. Recherches sur les marqueurs moléculaires de l’arôme de « fruits cuits » des raisins et des vins rouges issus des cépages Merlot et Cabernet-Sauvignon. Approche sensorielle, analytique et agronomique. *Thèse de doctorat* de l'Université de Bordeaux.

Berli F., Fanzone M., Piccoli P. and Bottini R., 2011. Solar UV-B and ABA are involved in phenol metabolism of *Vitis vinifera* L. increasing biosynthesis of berry skin polyphenols. *J. Agric. Food Chem.*, **59,** 4874-4884.

Brisson N. and Levrault F., 2010. Le Livre Vert du projet CLIMATOR. Ed. ADEME. 334 p.

Celette F., Findeling A. and Gary C., 2009. Competition for nitrogen in an unfertilized intercropping system: the case of an association of grapevine and grass cover in a Mediterranean climate. *Eur. J. Agron.*, **30,** 41-51.

Darriet P., Pons A., Allamy L., Schüttler A., van Leeuwen C. and Thibon C., 2016. *Quels impacts attendus du changement climatique sur les composés aromatiques et leurs précurseurs ?* 3[èmes] assises des vins du Sud-Ouest, IFV, Toulouse, 14 janvier 2016.

Duchêne E. and Schneider C., 2005. Grapevine and climatic changes: a glance at the situation in Alsace. *Agron. Sustain. Dev.*, **25,** 93-99.

Friend A. and Trought M., 2007. Delayed winter spur-pruning in New Zealand can alter yield components of Merlot grapevines. *Aust. J. Grape Wine Res.*, **13,** 157-164.

Hannah L., Roehrdanz P.R., Ikegami M., Shepard A.V., Shaw M.R., Tabor G., Zhi L., Marquet P.A. and Hijmans R.J., 2013. Climate change, wine, and conservation. *Proc. Natl. Acad. Sci. USA*, **110,** 6907-6912.

IPCC, 2014. Climate Change 2014, synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Core writing team R. Pachauri and L. Meyer Eds. IPCC, Geneva, Switzerland, 151 p.

Kliewer W. and Dokoozlian N., 2005. Leaf area/crop weight ratios of grapevines: influence on fruit composition and wine quality. *Am. J. Enol. Vitic.*, **56,** 170-181.

Lebon E., Dumas V., Pieri P. and Schultz H., 2003. Modelling the seasonal dynamics of the soil water balance of vineyards. *Funct. Plant Biol.*, **30,** 699-710.

Marguerit E., Brendel O., Lebon E., van Leeuwen C. and Ollat N., 2012. Rootstock control of scion transpiration and its acclimation to water deficit are controlled by different genes. *New Phytol.*, **194,** 416-429.

Martinez-Lüscher J., Sanchez-Dias M., Delrot S., Aguirreolea J., Pascual I. and Gomès É., 2014. Ultraviolet-B radiation and water deficit interact to alter flavonol and anthocyanin profiles in grapevine berries through transcriptomic regulation. *Plant Cell Physiol.*, **55,** 1925-1936.

Medrano H., Tomás M., Martorell S., Escalona J.M., Pou A., Fuentes S., Flexas J. and Bota J., 2015. Improving water use efficiency of vineyards in semi-arid regions. A review. *Agron. Sustain. Dev.*, **35,** 499-517.

Mercier V., Payen S. and Scholasch T., 2012. Use of sap flow measurement to characterize Terroir effect on vineyards. In *AGU Fall Meeting Abstracts*, **1,** 1592.

Moisselin J.-M., Schneider M., Canellas C. and Mestre O., 2002. Les changements climatiques en France au XX[e] siècle : étude des longues séries homogénéisées de données de température et de précipitations. *Météorologie*, **38,** 45-56.

Ollat N. and Touzard J.-M., 2014. Impacts and adaptation to climate change: new challenges for the French wine industry. *J. Int. Sci. Vigne Vin*, **Special issue (climate change),** 75-78.

Ollat N., Peccoux A., Papura D., Esmenjaud D., Marguerit E., Tandonnet J.-P., Bordenave L., Cookson S., Barrieu F., Rossdeutsch L., Lecourt J., Lauvergeat V., Vivin P., Bert P.-F. and Delrot S., 2015. Rootstocks as a component of adaptation to environment. In: Grapevine in a changing environment: a molecular and ecophysiological perspective. Eds. Geros H., Chaves M., Medrano H. and Delrot S., Wiley-Blackwell, pp. 68-108.

Parker A., Garcia de Cortazar Atauri I., van Leeuwen C. and Chuine I., 2011. General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera* L. *Aust. J. Grape Wine Res.*, **17,** 206-216.

Parker A., Hofmann R., van Leeuwen C., Mclachlan A. and Trought M., 2014. Leaf area to fruit mass ratio determines the time of veraison in Sauvignon blanc and Pinot noir grapevines. *Aust. J. Grape Wine Res.*, **20,** 422-431.

Parker A., Hofmann R., van Leeuwen C., Mclachlan A. and Trought M., 2015. Manipulating the leaf area to fruit mass ratio alters the synchrony of total soluble solids accumulation and titratable acidity of grape berries. *Aust. J. Grape Wine Res.*, **21,** 266-276.

Peyrot des Gachons C., van Leeuwen C., Tominaga T., Soyer J.-P., Gaudillère J.-P. and Dubourdieu D., 2005. Influence of water and nitrogen deficit on fruit ripening and aroma potential of *Vitis vinifera* L. cv Sauvignon blanc in field conditions. *J. Sci. Food Agric.*, **85,** 73-85.

Pieri P., Riou C. and Dubois C., 1999. Competitions for nitrogen and water in two vine-grass systems - application of a water balance model. *Acta Hortic.*, **493,** 89-96.

Reynolds A. and Vanden Heuvel J., 2009. Influence of grapevine training systems on vine growth and fruit composition: a review. *Am. J. Enol. Vitic.*, **60,** 251-268.

Roby J.-P., van Leeuwen C. and Marguerit E., 2008. Références Vigne. Références technico-économiques de systèmes de conduite de la vigne. 2e édition. Ed. Synthèse Agricole - Lavoisier, 269 p.

Sadras V. and Moran M., 2012. Elevated temperature decouples anthocyanins and sugars in berries of Shiraz and Cabernet Franc. *Aust. J. Grape Wine Res.*, **18**, 115-122.

Santesteban L., Miranda C., Urrestarazu J., Loidi M. and Royo J.B., 2016. Severe trimming and enhanced competition of laterals as a tool to delay ripening in Tempranillo vineyards under semiarid conditions. *OENO One*, **50,** *in press*.

Schöffling H. and Deroo J., 1991. Méthodologie de la sélection clonale en Allemagne. *J. Int. Sci. Vigne Vin*, **25,** 203-227.

Schultz H., 2000. Climate change and viticulture: a European perspective on climatology, carbon dioxide and UV-B effects. *Aust. J. Grape Wine Res.*, **6,** 2-12.

Schultz H., 2003. Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown *Vitis vinifera* L. cultivars during drought. *Plant Cell Environ.*, **26,** 1393-1405.

Schultz H., Löhnertz O., Bettner W., Balo B., Linsenmeier A., Jähnisch A., Müller M., Gaubatz B. and Varadi G., 1998. Is grape composition affected by current levels of UV-B radiation? *Vitis*, **37,** 191-192.

Shapland T., Snyder R., Smart D. and Williams L., 2012. Estimation of actual evapotranspiration in winegrape vineyards located on hillside terrain using surface renewal analysis. *Irrig. Sci.*, **30,** 471-484.

Smart R., 1987. Influence of light on composition and quality of grapes. *Acta Hortic.*, **206,** 37-48.

Tomás M., Medrano H., Pou A., Escalona J.M., Martorell S., Ribas-Carbó M. and Flexas J., 2012. Water-use efficiency in grapevine cultivars grown under controlled conditions: effects of water stress at the leaf and whole plant level. *Aust. J. Grape Wine Res.*, **18,** 164-172.

van Leeuwen C. and Seguin G., 1994. Incidences de l'alimentation en eau de la vigne, appréciée par l'état hydrique du feuillage, sur le développement de l'appareil végétatif et la maturation du raisin (*Vitis vinifera* variété Cabernet franc, Saint-Emilion, 1990). *J. Int. Sci. Vigne Vin*, **28**, 81-110.

van Leeuwen C. and Seguin G., 2006. The concept of terroir in viticulture. *J. Wine Res.*, **17,** 1-10.

van Leeuwen C., Tregoat O., Choné X., Gaudillère J.-P. and Pernet D., 2007. Different environmental conditions, different results: the role of controlled environmental stress on grape quality potential and the way to monitor it. In *Proceedings of the 13th Australian Wine Industry Technical Conference*, 29 July – 2 August 2007, Adelaide, Australia, pp. 39-46.

van Leeuwen C., Trégoat O., Choné X., Bois B., Pernet D. and Gaudillère J.-P., 2009. Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? *J. Int. Sci. Vigne Vin*, **43,** 121-134.

van Leeuwen C. and Roby J.-P., 2013. Préservation des ressources génétiques de la vigne et diversité des arômes. Nécessité d'une cohabitation entre sélection clonale institutionnelle, sélection massale et sélection clonale privée. *Rev. Œnol.*, **148,** 13-16.

van Leeuwen C. and Darriet P., 2016. Impact of climate change on viticulture and wine quality. *J. Wine Econ.*, **11,** 150-167.

Walker R., Blackmore D. and Clingeleffer P., 2010. Impact of rootstock on yield and ion concentrations in petioles, juice and wine of Shiraz and Chardonnay in different viticultural environments with different irrigation water salinity. *Aust. J. Grape Wine Res.*, **16,** 243-257.

Zhang X., Alexander L., Hegerl G., Jones P., Klein Tank A., Peterson T., Trewin B. and Zwiers F., 2011. Indices for monitoring changes in extremes based on daily temperature and precipitation data. *Wiley Interdiscip. Rev.: Clim. Change*, **2,** 851-870.