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GRAPEVINE AND CLIMATE CHANGE: WHAT ADAPTATIONS OF PLANT MATERIAL AND TRAINING SYSTEMS SHOULD WE ANTICIPATE?

Éric DUCHÊNE[1,2*], Frédéric HUARD[3] and Philippe PIERI[4,5]

1: INRA, UMR 1131 Santé de la Vigne et Qualité du Vin, 28 rue de Herrlisheim, BP 20507,
68021 Colmar Cedex, France
2: Université de Strasbourg, UMR 1131 Santé de la Vigne et Qualité du Vin, 28 rue de Herrlisheim, BP 20507,
68021 Colmar Cedex, France
3: INRA, US 1116 Agroclim, Domaine Saint-Paul, Site Agroparc, 84914 Avignon, France
4: INRA, UMR 1287 Écophysiologie et Génomique Fonctionnelle de la Vigne,
Institut des Sciences de la Vigne et du Vin, 210 Chemin de Leysotte, 33882 Villenave d'Ornon Cedex, France
5: Université Victor Segalen Bordeaux 2, UMR 1287 Ecophysiologie et Génomique Fonctionnelle de la Vigne,
Institut des Sciences de la Vigne et du Vin, 210 Chemin de Leysotte, 33882 Villenave d'Ornon Cedex, France

Abstract

The effects of climate change on grapevine physiology and wine characteristics are already visible and will very likely continue in the coming decades in all the grape growing regions of the world. The first observed and forecasted effect of climate change is an advance in phenological stages, with a ripening period occurring under warmer climatic conditions. This can significantly modify the characteristics of the berries, which will likely contain less anthocyanins, less acids, more sugars and presumably less aroma compounds. The effects of climate change on grapevine yield potential are more difficult to predict. On the one hand, there are uncertainties about the water deficits that will be experienced by the plants and, on the other hand, we lack quantitative relationships between water deficits and the formation of inflorescences and flowers. Moreover, direct effects of elevated atmospheric CO_2 concentrations on water use efficiency as well as on primary and secondary metabolisms also have to be considered. If the purpose of adaptation is to maintain the productivity of the vines and the typicity of the wines, changes in training systems and the use of new rootstock-scion combinations will be necessary. Modern tools for ecophysiological modelling and increasing knowledge about the genetic determinism of traits will provide a crucial basis for these adaptation processes

Key words: grapevine, climate change, adaptation

Résumé

Le changement climatique a déjà commencé à faire sentir ses effets et va vraisemblablement continuer à modifier, au cours des décennies à venir, le comportement de la vigne et les caractéristiques des vins produits dans tous les vignobles du monde. Le premier effet prévu, et déjà observé, est une avance des stades de développement, et donc une période de maturation des raisins se déroulant sous des conditions plus chaudes. Ce changement conduira à la production de raisins moins riches en anthocyanes et en acides, plus sucrés et vraisemblablement moins aromatiques qu'aujourd'hui. Les effets du changement climatique sur le potentiel de production sont plus difficiles à évaluer, non seulement à cause des incertitudes sur la satisfaction future des besoins en eau mais aussi car les relations entre l'alimentation en eau et la formation des inflorescences et des fleurs sont mal connues. Par ailleurs, l'augmentation des teneurs atmosphériques en CO_2 aura sans doute des effets directs sur l'efficience d'utilisation de l'eau mais également sur le métabolisme, en particulier secondaire, des baies. Si l'objectif de l'adaptation est de maintenir la productivité des vignes et la typicité des vins, il faudra envisager une évolution des modes de conduite ainsi que l'utilisation de nouvelles combinaisons porte-greffe-greffon.

Mots clés : vigne, changement climatique, adaptation

*Corresponding author:duchene@colmar.inra.fr

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INTRODUCTION

Agricultural production is highly sensitive to climatic change as both a change in environmental conditions and an increase in food demand are expected. Increasing food production in a warmer climate is a challenge for the whole planet (Paillard *et al.*, 2011). Wine production is not essential to satisfy human needs for food. However, in some European countries, such as France, a destabilization of grape and wine production will have significant direct impacts on farmers' incomes (Moriondo *et al.*, 2011 ; Webb *et al.*, 2008) and employment, but also indirect impacts on land use, landscapes, tourism activities and rural life in numerous regions.

Preserving grape and wine production in a changing climatic context is a subject of growing interest in many countries. In this article, we provide a synthetic overview of the challenges that we will have to face in order to adapt grape production to climate change.

TO WHAT SHOULD WE ADAPT ?

Before trying to develop adaptation strategies, it is necessary to identify the aspects of grape production that are susceptible to climate change.

A shift in developmental stages

The first reported effect of temperature increase is an advance in developmental stages, observed worldwide (Duchêne and Schneider, 2005 ; Jones and Davis, 2000 ; Jones *et al.*, 2005a ; Petrie and Sadras, 2008 ; Ramos *et al.*, 2008). The link between grapevine phenology and temperature is so close that it has been used, on the one hand, to assess temperatures from the past centuries (Chuine *et al.*, 2004) and, on the other hand, to propose models for predicting developmental stages in the future (Brisson and Levrault, 2010 ; Duchêne *et al.*, 2010 ; Garcia de Cortazar Atauri, 2006 ; Webb *et al.*, 2007). An advance in developmental stages of 2 to 3 weeks by 2050 compared to the last 30 years is predicted by these models (Brisson and Levrault, 2010 ; Duchêne *et al.*, 2010 ; Moriondo *et al.*, 2011 ; Webb *et al.*, 2007). The advance in maturity stage could even reach two months by the end of the century in certain areas of Tuscany, Italy (Moriondo *et al.*, 2011) !

However, these predictions are uncertain, not only because of the diversity of climatic scenarios and models used, but also because the effects of high temperatures on grapevine phenology, sometimes combined with water stress, are not well characterized. As an example, the evolution of observed veraison dates in Alsace has been faster than in simulations (Figure 1). As a consequence of earlier veraison dates, berry ripening occurs, and will occur, earlier in summer, under higher temperatures, which can have significant impact on berry quality parameters.

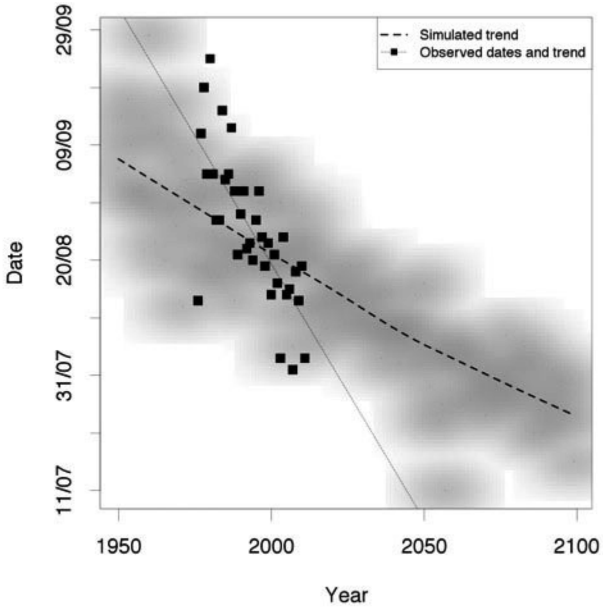

Figure 1 - Observed (black squares) and density cloud of simulated veraison dates for Riesling in Colmar. A1B scenario, MétéoFrance ARPEGE-Climat model, Weather type (WT) downscaling method.

An increase in total biomass ?

Besides effects on grape quality, climate change can have quantitative effects on grape production. Increasing concentrations of CO_2 and higher radiation levels are expected to increase the biomass production potential despite a shorter developmental cycle (Bindi *et al.*, 1996 ; Bindi *et al.*, 2001 ; Garcia de Cortazar Atauri, 2006 ; Moutinho-Pereira *et al.*, 2009). However, the expected increase in total biomass might be limited in the future by rainfall distribution and water availability, especially at the end of the growth cycle (Garcia de Cortazar Atauri, 2006).

Uncertainties about future fruit biomass

The effects of climate change on fruit biomass (*i. e.*, yield) are more difficult to anticipate than on total biomass production. Using statistical models, Santos *et al.* (2011) state that climate change should benefit grape yield in the Douro region in Portugal, whereas Lobell *et al.* (2006) in California anticipate a decrease, more pronounced for wine grapes than for table grapes. With mechanistic models, conclusions are very dependent on the regions studied (Garcia de Cortazar

Atauri, 2006) and the climatic datasets used (Bindi *et al.*, 1996). In the South of France and Italy, a decrease in yield potential is expected in the future (Bindi *et al.*, 1996; Garcia de Cortazar Atauri, 2006; Moriondo *et al.*, 2011).

Yield is the product of the number of berries multiplied by their individual weight and berry growth is determined by the number of seeds per berry (Dai *et al.*, 2009). Fruit formation is the consequence of qualitative events taking place over two growing seasons and determining whether an inflorescence is initiated or not, whether a berry sets or not, and whether a seed develops or not. The final yield is also dependent on quantitative variables such as the number of flowers per inflorescence or the berry growth rate. We are not aware of models able to integrate all the steps of yield components formation.

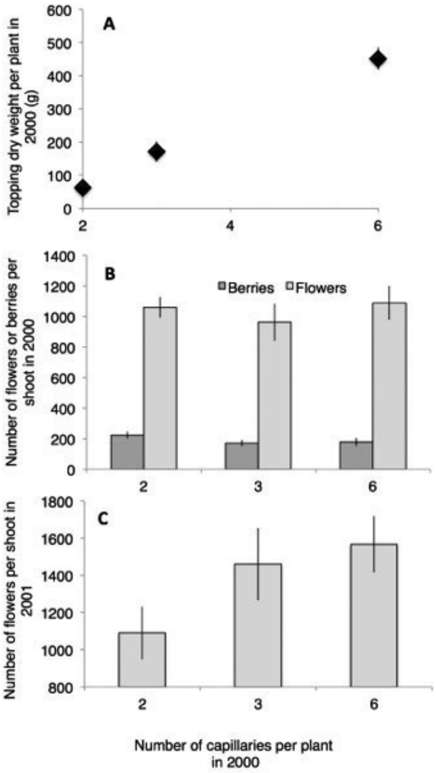

Figure 2 - Greenhouse experiment with Grenache grown in 80-l containers. Two, three or six capillaries were left for water supply one week before flowering in 2000. The same containers were well watered in 2001. (A) Total biomass dry weight removed from the plants above the stalks in 2000. (B) Number of flowers and number of berries per shoot in 2000.
(C) Number of flowers per shoot on the same plants in 2001. Bars represent standard errors.

To focus on flowers formation, we know that the number of flowers per plant or per m^2 can be a limiting factor of the number of berries (Duchêne *et al.*, 2001). This variable depends on the number of flowers per inflorescence and on the number of inflorescences per shoot, and climate change can affect both variables. Indeed, it has been demonstrated that the higher the temperatures around budburst, the lower the number of flowers per inflorescence (Keller *et al.*, 2010; Petrie and Clingeleffer, 2005; Pouget, 1981). Frost damage around budburst can also reduce the number of inflorescences but we have no clear assessment of this risk in the future: whilst the increase in the mean temperature can be evaluated, determining the frequency of the number of days below a threshold over a given period in the future is more speculative. Moreover, budburst is the phenological stage for which the prediction models are the least reliable: there is not only an influence of the pruning date (Martin and Dunn, 2000), but also an effect of the diameter of the canes left after pruning (Duchêne, unpublished data). In our simulations, the risk of frost after budburst was too variable, depending on the model and the climatic scenario used for budburst prediction, to draw any clear conclusion. It is, however, worth noticing that this risk did not always decrease.

High temperatures and high light intensity during the floral initiation process can increase the number of inflorescences (Buttrose, 1970), whereas a water deficit can have strong opposite effects (Buttrose, 1974; Matthews and Anderson, 1989). In a greenhouse experiment in Colmar, 5-year old Grenache plants were grown in 80-l containers in a sand-perlite mixture and irrigated with a complete nutritive solution through capillaries. To test the effects of water availability on growth and yield components over two seasons, three levels of water supply were studied by leaving 6, 3 or 2 capillaries per container. The experiment started on 12 May 2000, a few days before flowering (19 May 2000). During the first year, plant growth was closely linked to water supply (Figure 2A). On the contrary, during the same season, the number of flowers and the number of berries per shoot were not significantly affected (Figure 2B). During the following year, no water restriction was applied, but the number of flowers was significantly reduced in plants where only 2 capillaries per container were used during the previous season (Figure 2C). The lack of correlation between the level of biomass production in 2000 and the number of flowers in 2001 suggests a threshold effect of water stress on shoot fertility. These results emphasize the importance of possible future water deficits on grape yield: not only direct effects on berry growth (Hardie

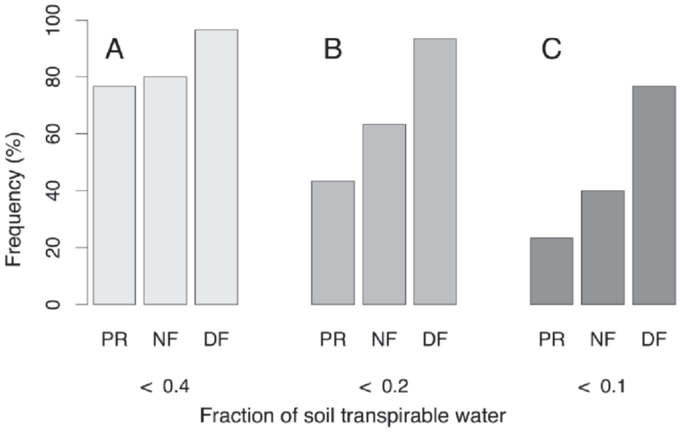

Figure 3 - Frequency of years with moderate (A), severe (B) and very severe drought stress (C) during the 35 days after veraison.

Riesling, A1B scenario for Colmar, Quantile-Quantile (QQ) downscaling method. PR: present 1975-2005, NF: near future 2020-2050, and DF: distant future 2070-2100.

and Considine, 1976 ; Matthews and Anderson, 1989), but also effects on the yield potential during the following growing season.

An extensive simulation exercise of future water availability in France was conducted within the framework of the "Climator" project (Brisson and Levrault, 2010). The overall conclusion was that, over the flowering to harvest period, the fulfilment of grapevine water needs (real evapotranspiration/maximal evapotranspiration) will not be greatly reduced but less water will return to the environment under the vineyards in the future. Nevertheless, it is likely that the frequency of years with severe drought stress at the end of the season will increase in the future (Figure 3).

Expected effects on grape and wine quality

The main concern about climate change is berry and wine quality. High temperatures accelerate the degradation of organic acids, but the effects are smaller on tartaric acid concentrations than on malic acid concentrations (Buttrose *et al.*, 1971 ; Kliewer, 1971). Varieties whose berries contain high quantities of tartaric acid should then be less sensitive to climate change. High temperatures also impair the accumulation of anthocyanins in berries (Kliewer, 1970 ; Mori *et al.*, 2007). There are indirect results showing that increasing temperatures are generally unfavourable to wine quality (Jones *et al.*, 2005b ; Moriondo *et al.*, 2011 ; Tonietto and Carbonneau, 1998, 2004), but, until now, there are no specific data on the effects of high temperatures on aroma compounds. Bureau *et al.* (2000) studied the effects of light environment on aroma compounds by comparing bunches exposed to the sun, bunches shaded by leaves and bunches shaded by black cloths. They quantified, in particular, molecules of the terpenol family, which participate in muscat-like aromas. The highest terpenol content was observed in the naturally shaded bunches and the lowest in the artificially shaded bunches. The authors suggested that these differences could be related to a modification of the red/far red ratio and/or to the temperatures recorded around the bunches (Figure 4). This is in agreement with findings from Reynolds and Wardle (1993) showing that cool growing sites were more favourable to monoterpenes accumulation than warm growing sites.

Climate change is primarily the result of an increase in atmospheric CO_2 concentrations. In FACE

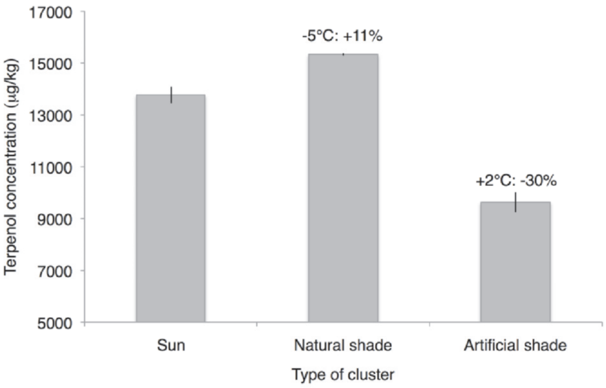

Figure 4 - Terpenol content of Muscat de Frontignan berries according to the type of cluster.

Data from Bureau *et al.*, 2000, year 1996.

Bars represent standard errors. Data above the bars are differences with the control "sun" treatment.

experiments, elevated CO_2 concentrations had little effect on the concentrations of primary metabolites (*i. e.*, sugars and acids) of berries (Bindi *et al.*, 2001 ; Goncalves *et al.*, 2009). On the contrary, Goncalves *et al.* (2009) provide results where elevated CO_2 concentrations modified the profile of secondary metabolites in wines.

WHAT IS ADAPTATION ?

The second question after "to what should we adapt ? is "what should be our goals for adapting grapevine cultivation to climate change ? The current response is to try to maintain the same wine production volume and typicity in the actual grape growing areas in the future, but other points of view are possible. For instance, as new areas will be suitable for grapevine cultivation (Malheiro *et al.*, 2010 ; Moriondo *et al.*, 2011 ; White *et al.*, 2006), national policies could be to maintain the wine production volume and the global income at the whole country level.

At a regional scale, the ultimate solution for wine growers to maintain their income could be the replacement of grapevine by new and more profitable crops. It could also be a change in the type of wine produced, moving from white to red wine production, for example. The time scale for these possible changes is, however, of particular importance as grapevine growing and wine making require long-term investments and specific know-how. It will take decades before new areas that will be suitable for grapevine cultivation in the future produce and sell significant quantities of wines of recognized quality. In the current grapevine cultivation areas, training systems can be modified in the short term (10-15 years), but changes in the varietal choice, especially for newly bred genotypes, will be effective only in the medium term (30-40 years). Speculating on long-term adaptation might be pointless considering all the uncertainties on climate toward the end of the century, but also on all the possible political and sociological events in the meantime. As a matter of fact, adaptation is likely to depend more on sociological and economic factors than on technical issues. Developments in European production rules as well as changes in global wine demand and production can modify wine market balance and trade opportunities for the current grape growing areas.

From another point of view, adaptation could also be made easier by the increasing consumer demand for pesticide-free grapes and wines. The idea of changing the traditionally used cultivars for new genotypes resistant to fungal diseases opens the gate to a more significant policy of varietal evolution.

Changing production practices will, however, have a financial cost and not all grape growers will have the ability to make additional investments. Local policies could hence have a crucial role in sustaining, or not, adaptation processes.

LOOKING FOR COOLER RIPENING CONDITIONS

If we consider that adaptation should primarily aim to maintain local wine typicity, the first objective is to develop solutions where grape ripening will occur under similar temperature conditions as at present. In the context of global warming, this means looking for cooler ripening conditions. How much cooler ? The forecasted order of magnitude of temperature increase during ripening by the middle of the century ranges from 2 °C (Brisson and Levrault, 2010) to 6 °C (Duchêne *et al.*, 2010 ; Webb *et al.*, 2007) according to the areas studied and the models and scenarios used. This increase is the result of both temperature increases in summer and shifts towards earlier veraison dates (Duchêne *et al.*, 2010 ; Webb *et al.*, 2007).

A first local adaptation would be to move grapevine cultivation to higher elevations (Caffarra and Eccel, 2011 ; Moriondo *et al.*, 2011). With a lapse rate of -6,5 °C/km (Standard Atmosphere, ISO 2533:1975), grapevine cultivation should move 600 m higher to compensate for a 4 °C increase. This, of course, is not possible everywhere, and when possible, the suitability of mountain soils for grape growing will be of great concern.

Planting grapevine on north-facing slopes is another solution that will depend on land availability. In a study in Alsace, the difference in veraison timing for a Gewurztraminer x SO4 combination at the same elevation (310-330 m) was 5 days between a south and a north-north-east slope (Lebon, 1993). This is a significant value at the present time but not sufficient when compared to the expected shifts, closer to 15-20 days by the mid-century (Duchêne *et al.*, 2010).

New training systems could provide complementary solutions. During the last decades, the main objectives of experiments on training systems were, on the one hand, to increase the photosynthetic efficiency of the canopy by increasing the leaf area and, on the other hand, to increase the light exposure of the grapes. Training systems should now be reconsidered with opposite objectives : on the one hand, decreasing the water demand by reducing the leaf area whilst maintaining an adequate sugar content in the berries and, on the other hand, leaving the grapes in shade as much as possible. 3D-modelling of training systems

(Louarn *et al*., 2008b) coupled with models allowing the calculation of organ by organ energy balance can help in the design and virtual testing of new training systems before planting experiments in the vineyard (Louarn *et al*., 2008a).

MAINTAINING THE YIELD LEVEL

An essential condition for a sustainable viticulture in the future is that grape growing has an economic interest (*i. e.*, generates income). We have few reliable data on the possible evolution of yield level. We have already mentioned a number of risks for the potential number of flowers : frost, high temperatures around budburst or drought stress during the period of floral initiation. There is no evidence that fruit set will be affected by climate change, but berry growth can be impaired by water deficits in the early stages of growth (Matthews and Anderson, 1989). The higher climatic demand for water will be compensated by an increase in water use efficiency following the rise in atmospheric CO_2 concentration (Manderscheid and Weigel, 2007 ; Schultz, 2000), but estimating the photosynthetic capacities of grapevine in the future is still a challenge. The most straightforward solutions to maintain grapevine production in the future are, first, to find the best-adapted scion x rootstock combination and, second, to irrigate the vineyards. Knowledge and technical issues should not be limiting factors for implementing irrigation, but financial costs as well as issues around water use might prevent the development of such a practice. A “no regret” policy is certainly to focus research programs on scion x rootstock x training systems that will result in efficient water management.

IMAGINING BETTER ADAPTED GENOTYPES

Besides changing cultivation zones and training systems, using new genotypes (both for scion and rootstock) is potentially a powerful adaptation strategy as grapevine is already grown today in warm regions around the globe. Providing that a change in the type of wine produced is accepted, finding scion x rootstock x training system combinations able to produce commercial quality wines for the current grape growing regions in France is a reasonable goal. It is, however, difficult to guarantee that the production volume will be the same as today. The main challenge will be to find varieties able to produce wines with the same organoleptic profile. With the idea of creating a new genotype that would be able to produce wines with characteristics similar to wines currently produced in Alsace, we have evaluated the range of phenological stages that could be found in progeny of a Riesling x Gewurztraminer (RixGw) cross (Duchêne *et al*., 2010). The veraison date of the “latest” virtual genotype from such a cross would be comparable to the veraison date of Ugni blanc or Muscat of Alexandria. However, in the future, veraison dates will continue to advance and occur during the first ten days of August in Alsace after the mid-century (A1B IPCC scenario). At the same time, we have calculated that the mean temperature during the ripening process of Riesling or Gewurztraminer is currently approximately 18°C. In the future, with the increase in summer temperatures, the period of such cool conditions will move from August to September. Consequently, whilst for the near future (2010-2040) the veraison date of our virtual late RixGw genotype will correspond to the date of cool ripening conditions, this date will occur approximately three weeks and one month after veraison for 2040-2070 and 2070-2100, respectively. In other words, it is likely impossible in the future, even with late ripening varieties, to find the same cool ripening conditions that we experience today (Duchêne *et al*., 2010). We should pay as much attention to the ability of genotypes to maintain certain characteristics under warm conditions as to phenological stages. Moreover, the temperatures during ripening tend to converge for early and late genotypes with the predicted temperature increase (Figure 5). This is understandable, as the maturation period will occur earlier in summer, when temperatures are at their highest level (Figure 6).

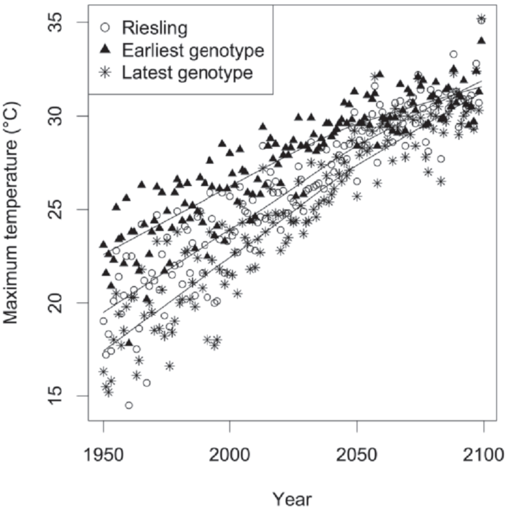

Figure 5 - Average maximum temperatures in Colmar during the 35 days following veraison for three genotypes. Empty circles: Riesling, Black triangles and stars: genotypes with the earliest and latest veraison dates, respectively, that we can imagine to breed from a Riesling x Gewurztraminer cross. A1B scenario, MétéoFrance ARPEGE-climat model, WT downscaling method.

Fortunately, phenology is not the only trait for which we can find some genetic variability. There is evidence that varieties of scions (Schultz, 2003) as well as rootstocks (Carbonneau, 1985 ; Marguerit *et al.*, 2012) can have different behaviour in response to water deficit.

Regarding berry quality, the tartaric acid content of berries is far less sensitive to high temperatures than the malic acid content (Kliewer, 1971) and there is a genetic variability for the tartaric/malic ratio in grapevine genotypes (Kliewer *et al.*, 1967 ; Shiraishi, 1995). Kliewer and Torres (1972) have also shown that the decrease in anthocyanin content under high temperatures was not equivalent for all the varieties. However, little is known about the genetic resilience of concentrations of aroma compounds to high temperatures.

CONCLUSION

Climate change will significantly modify the environmental conditions in most, if not all, of the vineyards in the world. The impact on wine production will depend on the region and on the type of wine produced, but in most grape growing regions in France, the priorities in terms of research, development and practices will change : instead of looking for better maturity through a higher leaf area and a better light exposure of the grapes, new training systems should now aim at minimizing the water demand whilst maintaining the grapes in the shade.

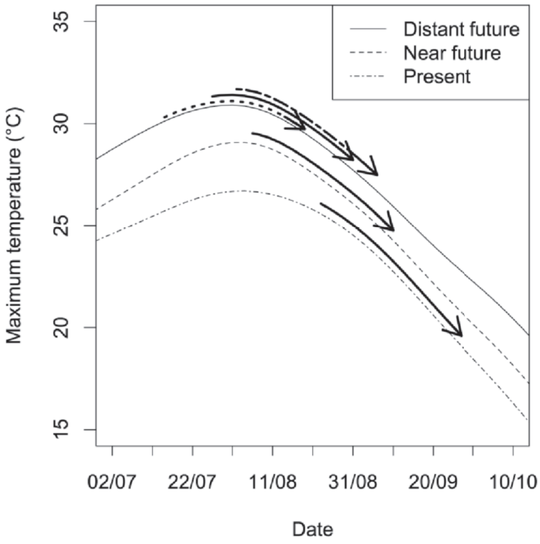

Figure 6 - Daily maximum temperatures averaged for three periods in Colmar: present (1975-2005), near future (2020-2050) and distant future (2070-2100). The plain arrows represent the corresponding ripening periods for Riesling. The dotted and dashed arrows represent the ripening periods in the distant future for the earliest and latest genotype, respectively (see Figure 5 for explanations). A1B scenario, MétéoFrance ARPEGE-climat model, WT downscaling method.

Climate change completely rearranges the map of genetic suitability. Northern vineyards will have a greater choice in the future and will need to evaluate new varieties for their conditions.

Modern biological techniques will also allow for designing and breeding new genotypes, tolerant to high temperatures and to water deficit.

One of the challenges for grape growing regions in the future will be to find efficient and robust technical solutions whilst maintaining a certain degree of differentiation. If all grape growing regions follow similar routes in adaptation, the profiles of many wines may tend to be more uniform than today.

Finally, adapting grapevine cultivation requires long-term choices, which can be difficult in an unstable and unpredictable environment.

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