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LACCAVE PROJECT

Vine growing and wine making in France challenging climate change

Foreword

Climate change is on the way. Because agriculture is highly dependent on climatic conditions, the vulnerability of this sector has to be considered with the highest priority. All predictions draw the conclusion that mitigation will not be sufficient and adaptation is crucial. Therefore the Institut National de la Recherche Agronomique (INRA) decided to support a multidisciplinary research program called ACCAF (Adaptation to Climate Change for Agrosystems and Forests) in order to evaluate the risks associated with climate change and extreme climatic events and to define strategies for anticipating and preventing the consequences of these crises.

Considering the socio-economic importance of the wine industry in France and its the strong dependence on climatic and geographical parameters, 23 laboratories from INRA, CNRS (Centre National de la Recherche Scientifique) and Universities brought together their expertise in order to investigate the issue of adaptation for this sector. All together, they elaborated the LACCAVE project (Long Term Adaptation to Climate Change in Viticulture and Enology). This project can be considered as a framework for French scientific studies addressing the question of adaptation. It should also be considered as a platform to develop bridges between the scientific community, extension services and the industry.

The project was launched on March 6-7, 2012 at a general meeting organized in Bordeaux under the umbrella of the ISVV (Institut des Sciences de la Vigne et du Vin). During two days, participants, members of the international scientific boards and representatives of the industry exchanged about the issue of climate change and the challenges in terms of biology, technics, innovations, adaptation, perception, economy, and social sciences.

One of the aims of the LACCAVE project is to build a common knowledge and to share perceptions about climate change. To that end, we decided to release a special issue of the Journal International des Sciences de la Vigne et du Vin, reporting some of the most important communications delivered at this meeting.

As coordinators of LACCAVE, we both consider networking and collective learning processes are the cornerstones for successful innovation and adaptation strategies. We try to run the LACCAVE project in this spirit. Therefore, we make the wish that the information made available to a large community through this document will contribute to the understanding of climate change impacts and the progress towards adaptation for the French wine industry.

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Contents

LONG-TERM ADAPTATION TO CLIMATE CHANGE IN VITICULTURE AND ENOLOGY: THE LACCAVE PROJECT

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Abstract

The LACCAVE project aims to study the impacts of climate change on the French wine industry and to analyze several adaptation strategies. It is a multidisciplinary project involving 23 different laboratories from INRA, CNRS and several French universities. The first part of this report describes the scientific context and rationale for the LACCAVE project and the known and predicted impacts of climate change on grape growing and berry ripening. Some directions for adaptation are also given. Finally, the 7 focus areas of the LACCAVE project are briefly described to give an overview of this ambitious study.

Key words: climate change, grape growing, wine making, adaptation, impact studies

Résumé

Le projet LACCAVE a comme objectif d'étudier l'impact du changement climatique sur la filière viti-vinicole française et d'analyser plusieurs stratégies d'adaptation. C'est un projet pluridisciplinaire qui implique 23 laboratoires de l'INRA, du CNRS et de plusieurs universités françaises. Cet article présente le contexte scientifique général du projet, ainsi que les impacts connus et prédits du changement climatique sur la culture de la vigne et la maturation des raisins. Des grandes stratégies d'adaptation sont également évoquées. Dans la seconde partie de l'article, les sept axes de travail du projet LACCAVE sont décrits brièvement afin de donner une idée générale de cette étude ambitieuse.

Mots clés: changement climatique, viticulture, œnologie, adaptation, études d'impact

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INTRODUCTION

The French wine industry, more than any other crop industries, needs to adapt to climate change. Given the socio-economic impact of wine production, the specific influence of climate on viticulture and wine quality, and the key issues of localization and innovations in this industry, INRA decided it was worthwhile to launch a multidisciplinary research project to explore not only the impacts of climate change on vine and wine but also the current and future adaptation strategies. The LACCAVE project brings together the expertise of 23 research laboratories and focuses on French wine producing areas. In close relationship with extension services and producer associations, this project aims at developing a common knowledge base on climate change issues, as well as gathering data, defining adaptation strategies and providing decision rules to address the critical issue of climate change adaptation for the wine industry.

CONTEXT

Climate change is already in progress. By the end of the XXIst century, the various simulations predict atmospheric CO_2 concentrations between 540 and 950 ppm. According to the IPCC (Intergovernmental Panel on Climate Change) expertise, average temperatures are expected to increase by 1.8 to 4 °C over the next century. With higher uncertainties, precipitations will increase slightly, along with drier summer in temperate zones, especially in Mediterranean countries. In addition to these average evolutions, climate change may increase spatial and temporal variability along with more frequent extreme events.

Even if reducing greenhouse gas emissions will likely have a positive impact on climate, climate change will go on because of the inertia of the earth's biophysical system and also because country policies are still not ambitious enough. Consequently, adaptation is crucial and should be considered as complementary to mitigation. Adaptation to climate change can be defined as the whole set of actions and processes that aim at adjusting natural and human systems in response to climate change in order to reduce its negative effects or take advantage of the positive ones. Even if climate change will generate costs to society, it will also bring new opportunities.

For these reasons, INRA has decided to support the multidisciplinary research program ACCAF (Adaptation to Climate Change for Agrosystems and Forests, INRA, 2011). The objective is to evaluate the risks associated with extreme climatic events and to define strategies for anticipating and preventing the consequences of such events., ACCAF also aims at (i) simulating the regional-scale impacts of climate change on agriculture and various ecosystems, (ii) understanding and controlling the major effects of climate change on biodiversity and ecosystem health, (iii) at adapting cultivated species and agricultural production systems to climate change, (iv) developing climate-friendly technological innovations that reduce greenhouse gas emissions, (v) identifying the costs and benefits of adaptation practices with regard to other issues (e.g., economic competitiveness, biodiversity, water and soil resources, quality), and (vi) defining common human organization pattern to enhance adaptive capacities to climate change.

WHAT DO WE KNOW ABOUT GRAPEVINE ?

Wine grapes (*Vitis vinifera*) are constrained to a narrow climatic range and consequently are especially sensitive to climate change, with potential effects on yield, quality and economic viability (Jones *et al.*, 2005). With the expansion of grapevine cultivation came the establishment of specific grape growing regions, whose climatic conditions played a decisive role in the production of typical wines from specific varieties and cultural practices (Schultz and Stoll, 2010). Climate traits, along with other environmental characteristics, have been used over time for the practical and legal delimitation of these regions or "terroirs". The French Appellation system took viticultural zoning one step further by adding regulations for practices and varieties to the legal definition of wine regions. Viticulture has developed very specific and codified relationships with geographical spaces and technologies. This is the reason why wine growing appears to be a "model agricultural system" allowing the evaluation of both the impacts of climate change and the implementation of adaptation strategies (Seguin, 2010).

The possible effects of climatic changes on grapevine development and ripening processes have been recently reviewed by several authors (Garcia de Cortazar Atauri, 2006 ; Holland and Smit, 2010 ; Duchêne *et al.*, 2010 ; Mira de Orduna, 2010 ; Schultz and Stoll, 2010). However, the long-term effects are difficult to predict, partially because many aspects (e.g., different varietal sensitivity regarding interactions between environmental parameters and plant adaptation mechanisms) are still largely unknown.

Temperature plays a major role in regulating plant phenology and there is a general agreement that the timing of all the phenological stages will be advanced in the future: budbreak should be 3 to 18 days earlier in the second half of the XXIst century and the ripening period should be 20 to 40 days earlier compared to the last 30 years (Duchêne *et al.*, 2010; Garcia de Cortazar Atauri, 2006; Webb *et al.*, 2007; Pieri, 2010). This shift towards earlier, warmer ripening periods will increase the impact of temperature on the ripening process. Based on changes in grapevine phenology, Garcia de Cortazar Atauri (2006) has shown that a temperature increase of 4-6 °C in southern France and 6-8 °C in northern France may be observed during the ripening period. Most climatic indices show that some areas in the north of France will become more suitable for viticulture (Malheiro *et al.*, 2010).

The impacts of climate change on biomass production and fruit development are more difficult to predict, because of the combined effects of several parameters and varietal differences. Despite the fact that photosynthetic activity will be enhanced by rising atmospheric CO_2 content, it is likely that carbon assimilation may be down-regulated by sink activity. Moreover, plant respiration will also be intensified (Schultz, 2000). In a free-air CO_2 enrichment (FACE) experiment with Sangiovese, leaf area and total vegetative dry weight were increased to a greater extent than fruit dry weight (Bindi *et al.*, 1996a; Bindi *et al.*, 1996b; Webb *et al.*, 2007) and yield response to CO_2 enrichment was negative when temperature and solar radiation were also increased. Moreover, the reproductive response of grapevines to temperature was shown to vary among cultivars (Dunn, 2005). A more vigorous vegetative development may also increase water consumption and affect canopy structure, which in turn will have negative effects on vegetative and reproductive growth. Plant water status is expected to decrease after 2050, with negative impacts mainly in the south of France (Pieri, 2010). The control of grapevine water balance under modified climatic conditions (high CO_2, high temperature, low water content) will also be a key issue and water use efficiency has been reported to increase under these conditions (Schultz and Stoll, 2010). Root development will probably be affected as well, as shown for *Picea abies* (Lebègue *et al.*, 2004).

Grape ripening will be strongly affected both directly by modified environmental parameters and indirectly by the effects of these parameters on whole plant physiology, source/sink relationships and canopy microclimate. Ripening would occur under much warmer conditions than today, with major impacts on berry content and suitability to elaborate the current types of wines (Duchêne *et al.*, 2010). An increase in berry sugar content has already been reported for the last decades of the XXth century (Duchêne *et al.*, 2005). This is likely due to the progressive increase of solar radiation before and during the ripening period. A significant temperature effect on berry acidity has also been reported. Combined with an increase in potassium uptake, grape juice pH is strongly impacted (Kliewer, 1971; Coombe, 1987). Large varietal differences have been observed in the response of titratable acidity and pH to heating (Sadras *et al.*, 2013). Polyphenolic and aroma compounds, which are crucial for quality, will be affected quantitatively and qualitatively as well (Mori *et al.*, 2007; Sadras and Moran, 2012). The interactions between various environmental parameters such as extreme temperatures and light intensities are critical for this kind of compounds (Tarara *et al.*, 2008). Ultimately, changes in radiation quality will also strongly impact grape composition (Lafontaine *et al.*, 2005).

Climatic changes will also influence the incidence of various pests and diseases, affecting both the epidemiology and the susceptibility of cultivars to these pathogens (Mira de Orduna, 2010; Salinari *et al.*, 2007; Pangga *et al.*, 2011).

Most experts have highlighted the complexity of the issue of climate change at physical, biological, technical, social, economic and cultural levels, especially for viticulture and wine production (Jones and Webb, 2010). So far, there has been a lot of research on the impacts of climate change on the physical and biological aspects of viticulture. However, the extent to which climate change represents a risk or opportunity depends also on the capacity of grape growers and wine makers to adapt to changing conditions and only few studies have investigated this capacity (Holland *et al.*, 2010). An assessment of wine growers' perception of climate change in three European countries showed that most growers have perceived the changes in climatic conditions that occurred so far (Battaglini *et al.*, 2009). Impacts on yield, quality, and incidence of pests and diseases were noted with slight variations among countries. Options for adaptations varied among countries and the readiness to adopt adaptation measures was correlated with the degree of changes already planned, independent of climate change. Vulnerability approaches using system-based assessment showed that many factors have to be taken into account to evaluate the risks perceived by producers and the adaptation options they selected (Holland and Smit, 2010).

Large variations in climatic conditions do exist within viticultural areas, as a result of geomorphology, land cover, and proximity of main water bodies and urban areas (Bois *et al.*, 2008). Environmental parameters (temperature, water, CO_2, soil mineral composition) will likely interact. Their combined effects on the numerous variety/rootstock combinations are difficult to predict, especially for fruit composition. Adaptation of technical practices and plant material will be crucial (van Leeuwen *et al.*, 2007; Ollat *et al.*, 2011). The relocation of vineyards to new areas would also represent an alternative. The adaptive capacity of the wine industry will be influenced by a number of economic, sociological and legal factors, and adaptive strategies will differ among wine regions (Hinnewinkel, 2007; Holland and Smit, 2010). Therefore, a global approach based on a combination of technological innovation, localization strategies and institutional changes is clearly needed to propose effective adaptation solutions.

THE LACCAVE PROJECT

LACCAVE is a 4-year project that aims at establishing a scientific framework to address climate change issues in viticulture. The project is coordinated by two scientists from Bordeaux and Montpellier and is organized in seven working groups. Over the course of the project, bridges will be built gradually between the working groups, and links with extension services and producer associations will be developed. LACCAVE is under the supervision of an international scientific board including scientists from Germany, Spain, USA, Brazil and South Africa. The different areas of focus are described below.

1. Characterization and perception of climate change

This working group aims at gathering and elaborating the basic information required for the project. By downscaling general climate prediction, it should provide regional climate simulations at different scale levels (small region, property) and for various periods of time (before 2050, from 2050 to 2100). It also aims at better evaluating how the various actors of the wine industry perceive climate change and at defining which parameters affect these perceptions. This information is crucial to develop adaptation strategies. In addition, this group will review existing knowledge on climate change for the project participants, considering their heterogeneity in terms of expertise and the need to share a common vision and a common vocabulary about climate change. Literature reviews will be released. Emphasis will be placed on plant health issues.

2. Physiological and genetic bases of grapevine adaptation to climate change

This working group aims at analyzing grapevine responses to major climatic parameters that may be affected by climate change (atmospheric CO_2 content, temperature, water) and at identifying the genetic mechanisms involved in such responses and the differences between scion and rootstock varieties. Traits related to phenology, vegetative growth, water consumption, berry development and fruit composition (sugars, acids, phenolic compounds and aromas) will be studied. The effects of modified berry composition and vineyard microflora on wine production processes will be analyzed as well. Results from the other research projects will be integrated in this working group using a systemic biology approach. This group will also work to coordinate experimental facilities to define common protocols for plant material description (phenotyping). The main challenge of this group is to elaborate modeling approaches that could be useful for vine performance simulations in future climatic conditions.

3. Development of technical innovations for adaptation to climate change

This working group aims at setting and studying technical practices to adapt vine growing and wine making processes to climate change. Enological practices will be considered to provide rapid direct answers to changes in berry composition. Several viticultural practices will be analyzed (plant density, soil management, training systems, pruning, fruit/leaf ratio), with a special focus on irrigation. The contribution of genetic diversity among existing scion and rootstock varieties will also be studied. One of the main objectives of this group will be to design cultural and varietal ideotypes based on grapevine requirements, achievements and adaptive potential.

4. Evaluation of the impact of technical innovations at a territorial scale

This working group aims at evaluating climate change impacts at a local scale (e.g., small wine growing region, water catchment area, terroir) taking into account current and new viticultural practices. It also aims at measuring the consequences of new adaptation practices (technical and migration) in terms of vineyard sustainability. Multicriteria evaluation methods including environmental parameters (water and soil resources) will be used for grape and wine typicity. The capacity and the limiting factors of producers to adopt adaptive practices will be studied by means of interviews and focus groups. Several case studies will be performed in different vineyards (Val de Loire, Alsace, and Languedoc Roussillon). Researchers will specifically explore the assumption that local scale is a relevant level of adaptation, by combining different levels of action (including innovations) and taking advantages of the diversity and variability of local resources.

5. Analysis of the evolution of economic strategies

Climate change will impact production costs and the relationship between quality and geographical origins. These factors are crucial for the competitiveness of the wine industry at local, national but also international scale. This working group aims at studying the effects of climate change on producer marketing strategies but also on consumer taste and willingness to pay for new types of wines. If consumers accept the impact of climate change on wine quality, the need for radical changes in technical system will be less important. If consumers do not accept it, then maintaining a defined wine quality will become a big challenge for producers and researchers. Competition between wine producing regions and the contribution of regulation will also be analyzed. As a complete analysis is not possible, the group will focus on the evaluation of consumer perception and producer strategies to cope with the demand and the new production conditions, considering the cost of adaptation. The consequences of climate change on the competitiveness of the French industry at the European level will be evaluated. Finally, regulation systems, and especially the Appellation system, will be questioned.

6. Data management and analyzes

This working group aims at providing the partners with data management support. Existing data bases and information systems will be identified. An attempt to design specific information systems with shared sub-units will be made. Methodologies for analyzing and integrating complex data will be provided to participants.

7. Elaboration of strategic scenarios for 2050

This working groups aims at conducting a foresight study to build and explore strategic scenario for the adaptation of the wine industry to climate change. These scenarios will provide a conceptual framework to guide the LACCAVE project and will be updated using the results and expertise of the different working groups. The originality of the approach is to start from 4 pre-defined adaptive scenarios: a conservative scenario, consisting of only marginal changes, to assess the impacts of passive adaptation; an innovative and technical scenario, focusing on changes in agricultural practices, to maintain existing vineyards; a migration scenario taking into account the possibility for vineyards to move spatially according to climatic conditions; and a zero-regulation scenario to test what happens when “anything is possible anywhere”. The scenarios developed will be submitted to producers in different French wine regions in order to open a debate on this issue and define realistic strategies for each region. Without any doubt, a single strategy will not work. Adaptation will occur in many steps and via a unique pathway in each situation. The project does not aim at providing final solutions but tools that will help develop strategies, research and policy making.

CONCLUSIONS

The LACCAVE project was launched in March 2012 during a general meeting held at ISVV (Institut des Sciences de la Vigne et du Vin) in Bordeaux. In a first attempt to build a common knowledge among the partners, the meeting was introduced with several lectures on key aspects of climate change related to vine growing and wine producing. These lectures aimed at illustrating the different components of the project. The main information presented then is now reported in this special issue of the Journal International des Sciences de la Vigne du Vin.

An overview of perception and concern from representatives of grower associations in 5 major French wine regions will first be presented. The relationship between climate and wine typicity will be illustrated at an international level with a special focus on Ibero-American grape growing regions. Then the issue of downscaling climatic predictions at small wine region scale relevant to the adaptation process will be developed. The main results of the Climator project will also be reported for vine growing. By linking climatic prediction and crop models, Climator provided the first simulation of the impacts of climate change on several agrosystems in France. The issue of plant health will be of primary concern. In the second part of the document, adaptation will be considered and key issues linked to adaptation processes in terms of decision making will be analyzed. Finally, the potential use of some technical innovations to cope with climate change will be presented. Focus will be placed on plant material, training systems and enological processes.

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CLIMATE CHANGE: PERCEPTIONS AND ISSUES FOR THE BORDEAUX WINE INDUSTRY

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VINEYARDS OF BORDEAUX AND CLIMATE CHANGE

The Bordeaux wine region is composed of 60 AOCs (*Appellations d'Origine Contrôlée*). It extends over 110 200 hectares of vines and brings together 7 900 AOC winegrowers, 42 wine cooperatives or cooperative unions, and 300 wine trade firms. It is characterized by a moderate oceanic climate (with mild winters and hot summers), very diverse soils, and a landscape marked by an important river system. Its noble varieties, on the edge of maturity, bring to the wines of Bordeaux their best expression, finesse and quality.

Many studies have shown the impact of climate change on the vineyards of Bordeaux:

- Increase in average temperatures in the Gironde Department with the maintenance of effect marked vintage (Goutouly, 2011),
- Shortening of the vegetative cycle (Bois, 2007),
- Early maturation (about 20 days earlier in the last 30 years).

The impact on the dates of harvest is real but hard to quantify. If technological maturity is reached early, the date of harvest is often delayed to achieve full phenolic maturity (Geny *et al.*, 2011). This trend, which has been observed for the past 20 years in Gironde, is in part related to the development of new tools to monitor grape maturity (phenolic maturity, berry tasting, pyrazine analysis, etc.). It is also related to the development of qualitative techniques (operations increase in leaf area, green harvesting, etc.), which helped improve berry maturation.

PERCEPTIONS AND ACTIONS OF THE SECTOR

To date, these climate changes had a relatively positive impact on the quality of Bordeaux wines: a more complete (if not fully complete) maturation of the grapes, richer in sugars and polyphenols, with less vegetal character, and, ultimately, more high-quality vintages. Concern is now focused on the decrease in total acidity, the increasing microbiological risk, and maintaining the typical characteristics and balance of the wine (Pons *et al.*, 2009). Other negative impacts include decreased vigor and changes in water and mineral supplies due to drier years and more frequent extreme climatic events (hail, heavy rain).

The profession has taken actions to mitigate (carbon footprint in 2008, Climate Plan launched in 2009, Environmental Management System approach launched in 2010) and adapt to climate change (choice of plant material to strengthen vigor and resistance to drought, night harvest, harvest and fermentation management). The profession supports many research programs on these topics.

ISSUES AND EXPECTATIONS OF THE SECTOR

In the medium term, recurring heat waves, comparable to that of 2003, are expected. There are several potential adaptation options:

- Choice of late maturing plant material (grape varieties, clones, rootstocks, etc.),
- Better management of water resources (grass cover, etc.),
- Integrated canopy management (green pruning, leaf removal, etc.),
- Precision viticulture (best implementation according to the precocity of the plots, etc.).

In the longer term, the use of certain practices (grass cover, etc.) should be limited until recommended with a view to quality research. More radical innovations will also have to be considered: modification of plant material and vine training system, use of irrigation, etc. If global warming goes beyond 2 °C, the major challenge will be to maintain the specificities of Bordeaux wines (i. e., “elegance and finesse”).

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The grape and wine sector faces one big challenge: adapt to climate change without moving the vineyards and without qualitative and economic loss. To succeed, it will need tools and knowledge to anticipate and innovate. Research is a priority - the main topics include knowledge and monitoring of the soil, plant material, vine physiology, drought resistance, and wine typicity.

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CLIMATE CHANGE AND IMPACT ON THE WINE INDUSTRY THE VAL DE LOIRE PERSPECTIVE

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Like all other wine regions, the Val de Loire is highly concerned about the issue of the impact of climate change on wine production. Concerns are related to the entire production process. However, beyond the answers or directions that scientific research could bring to the industry about climate variations, our ability to adapt is the most important challenge we have to face : building scientific knowledge and scenarios should allow us to anticipate and identify the various adaptation levers. It should also help us to characterize the limits of each lever, the critical points for which there is no solution, and finally the consequences, on a broad scale, on the wine types of our region (production, typicity, trading, etc.).

One of the main issues is our ability to maintain, at the long-term scale, the actual typicity of our wines. However, typicity is not a fixed trait and we wonder if this is the best way to deal with climate change. Indeed, typicity has been changing for ages and will continue to change in the future. The main question, thus, is whether this process will speed up and how it will impact the behavior of the actors (from growers to consumers) and their final acceptance of the necessary changes.

As a first step, more information is needed on global climate variability and on the combination of this variability with the trends currently observed in our vineyards, at a relevant scale for production activities. At terroir scale, climate variability is already very large and may even be larger than the one broadcasted for the next 50 to 100 years. We can therefore assume that, within a small area, some plots will be less sensitive to climate change than others and that, production conditions may remain unchanged in the future, providing some adaptations to local pedo-climatic conditions. Consequently, the characterization of spatial soil and climate variability at plot scale appears to be one of the key elements for anticipating climate change.

Vineyard performance is also linked to the interactions between environmental conditions (soil and climate) and plant material. Therefore, it is necessary to work on the issue of plant material as well. Our traditional varieties exhibit high genetic diversity, and germplasm conservation allows the maintenance of a large pool of phenotypic diversity. The selection of new clones, better adapted to future growing conditions (phenology, sugar content, acidity, etc.), is an important lever to sustain our traditional varieties over the long term. In addition, new rootstocks and varieties should be bred/selected for a better adaptation to future biotic and abiotic constraints.

Beyond the challenge of perennial practices (vineyard location and plant material), climate change adaptation is also linked to annual growing and oenological practices. Annual water status and thermal microclimate at the plant level should be managed in an integrated way (canopy management, soil management practices). It is necessary to develop innovative practices to address climate change, because the range of actual practices may not be large enough to cope with the projected precipitation and temperature changes. New practices or imported ones from other regions will represent a key aspect for adaptation. The same applies to the cellar with the efficient management of musts and wines composition (sugar, alcohol, acidity, phenolic compounds, aromas, etc.). The full range of physical, chemical and biological techniques should be mobilized to adapt to the new composition of grapes.

Furthermore, pest and disease management practices will have to be adapted to new constraints, such as new strains or new pathogens. The evolution of the life cycle of pathogens should also be taken into account. To that end, research should contribute to the development of adaptive pest/disease management practices and provide some sustainable solutions such as plant material resistant to the most important plant

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pathogens. However, this latter solution will result in a drastic change in wine typicity and will need to be socially accepted. These new varieties should be introduced slowly such as to avoid any abrupt changes.

The acceptance of change is therefore as important as the development of new adaptive techniques. Indeed, the adoption by growers of these new techniques will require the acceptance of their consequences on work organization and wine quality. Finally, the consumers will represent the critical step for the acceptance of new wines and new production conditions. Therefore, social changes (environmental protection, human health, regulations…) also have to be taken into account. Acceptance/refusal will depend on the rate of these changes and the ability of human being to adapt and learn.

CLIMATE CHANGE IN THE RHONE VALLEY

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The Rhone Valley vineyard area extends over about 71 000 ha. Its 5000 wineries and farms produce every year over 3.1 million hectoliters (90 million gallons) - 400 million bottles - of wine, essentially red wines but also white and rosé wines.

This big wine growing region of the Mediterranean area produces mainly "appellation" wines (premium quality wines produced in a specific area) but also "vin de Pays" and table wines. Numerous grape varieties (>30 different ones) are used to produce many different types of wines, including Grenache and Syrah, which are the most frequent ones.

CLIMATIC CHANGE IS ALREADY A REALITY

Changes in climate have already been observed in our region :

- Temperature increase of 1,1 °C within the last 30 years ;
- Reduction in spring and summer rainfall (Cirame) ;
- A feeling that extreme climatic events occur more frequently than before (heat wave of summer 2003, winter freeze of 2012, hail, violent storms, summer droughts).

Changes have also been observed in the vineyard and in grape and wine composition :

- Advanced phenology and earlier harvest dates (Inter Rhône) ;
- Increased alcohol content in wines ;
- Decreased titratable acidity.

As of today, grape growers have been able to adapt their vineyard management and wine making techniques in order to keep elaborating typical, rich and concentrated wines, despite the current trend towards « more ripened » harvest.

However, during the same period of time, yield has suffered a regular erosion. Climate change seems to partially explain this decline, counting on the reduction in rainfall regime during the vegetative period and the post harvest reserve restoration period.

In the medium to long term, given the climate change forecasts, current adaptations might no longer respond efficiently and there will be a need for deeper transformations of the vineyard. Indeed, the STICS (*Simulateur mulTIdisciplinaire pour les Cultures Standards*) modeling calculations performed by Garcia de Cortazar Atauri (2006) predict an increase in water and temperature stresses along with a decrease in yield by 35 % for the year 2100.

A more recent study, again using STICS model, confirms the yield decrease, due essentially to lower water content in the soils that are today the most comfortably supplied (Boutin, 2011 - Casdar Project). However, this work has failed to identify any positive techniques (e.g., grapevine canopy control, grape thinning, changing vine planting density or delaying pruning time) to control the impact of climate change on vines. Only irrigation was shown to partially balance the negative impacts of the climatic change simulations displayed.

In order to protect the quality and competitiveness of our vineyards, not only for the Rhone Valley region but also for the whole Mediterranean area, it thus appears necessary to further develop irrigation and to conduct research on adaptation of terroirs, plant material, vineyard management, drought resistance and wine making processes.

For this purpose, a national and international collaboration seems to be necessary, considering both the ambitious program needed and the grape growers' expectations.

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VINEYARDS OF LANGUEDOC-ROUSSILLON: WHAT ADAPTATION TO CLIMATE CHANGE?

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In the French Mediterranean regions, climate change is expected to result in warmer and drier summers, milder winters, and shorter rainy seasons (autumn-winter) combined with higher rainfall variability. The "semi-arid" nature of the Languedoc-Roussillon climate should be more pronounced, accentuating water and temperature stress for the vines.

The vineyards of our region are already experiencing the effects of this climate change. Seven of the past ten years are marked by summer or autumn drought. The average harvest is earlier by fifteen days comparing to the last century. Observations carried out by INRA show that vine water deficits are much more frequent during the summer period in the Languedoc plain. These deficits can affect the yield and quality potential of the grapes. Wines have also changed their aromatic profile, including higher alcohol content and lower acidity. Finally, the climate varies more from one year to the next, increasing the variability between vintages.

Such impact of climate change is an important issue because the wine industry plays a significant role in the regional economy. Wine is the main export product of our region, which is the first exporter of French wines in terms of volume. Two-thirds of farms are specialized in viticulture and 100,000 people in 2009 performed an activity directly or indirectly related to wine. Wine production continues to play a role in the social life of many Languedoc villages. It also contributes to the culture and landscape of the region, with positive effects on tourism, another important economic sector. Adapting to climate change is thus an additional challenge for our wine industry, which must continue to innovate through partnership programs dedicated to research and experimentation.

Irrigation is one of the innovative ways to address climate change in Languedoc-Roussillon. The region already has 85,000 hectares of irrigated crops, including 23,000 for the vines, i.e., 10 % of the vineyards, when in other countries most of the vineyards are fully irrigated. Although the irrigated area is still limited, Languedoc-Roussillon has become the French leader on the irrigation issue, thanks to projects cofunded by the French government and the Regional Council. Unlike other irrigated crops, vine needs small volumes of water per hectare (around 500 m^3). Our goal is to develop an irrigation management system compatible with sustainable development, defining water supply according to the type of wine and model simulations of water stress.

However, irrigation is not available everywhere and may compete with the water needs of the growing population of Languedoc-Roussillon. Today, teams are concentrating their efforts in other areas of research, including "dry strategies" research on plant material, soil management, adaptation of technical itineraries, agroforestry, wine making methods, etc. Needs and solutions must be tailored to the localisation (hills vs plains), the products (PGI (Protected Geographical Indication) or AOC (*Appellation d'Origine Contrôlée*) wines, wine without GI, organic wine, grape juice, etc.) and the economic organization (private or cooperative cellar, part timer or professional). The diversity that characterizes our region generates a multiplicity of experiences, practices and knowledge. The region can also benefit from many players working in research and development: INRA, Montpellier SupAgro, the French Institute of Vine and Wine, wine trade organizations, Chambers of Agriculture, the Cooperative Institute for Wine, and many cooperatives and private companies contributing to the regional wine industry. Future policies should enhance and facilitate cooperation between all of these parties to enable the vineyards of Languedoc-Roussillon adapt to climate change.

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CLIMATE CHANGE IN CHAMPAGNE

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A comparison between climate statistics collected in Reims or Epernay over the 1991-2012 period and the 30-year 1961-1990 reference period was used to evaluate current climate change.

TEMPERATURES

They have shown significant increase since the late 1980's. It is the fastest changing climatic parameter.

In Epernay, average temperatures have increased by 1.1 °C (11.5 °C) for the whole year, by 1.2 °C over the April-September period (16.4 °C) and by 1 °C over the grape maturation period (August-September) with 17.6 °C. The Huglin index (1) has gone from 1,590 degree-days to 1,795 degree-days, equivalent to Bordeaux for the 1961-1990 reference period.

The number of hot days (temperature above 30 °C) over the year has gone up from 7.3 to 12.6, i. e. a 73 % increase. Over the maturation period (August-September), the same indicator has risen by 76 % from 2.9 to 5.1 days. Over the latter period, if the 10 days advance due to global warming is taken into account, hot days number grows from 1.6 to 3.7; that is a frequency multiplied by 2.3.

Winter frost days in Reims have decreased from 4.2 days, with a minimum temperature in the shade below -10 °C, to 2.4 days, meaning a fall of 43 % of the risk. The average annual absolute minimum has gone from –12.9 °C to -11.8 °C. It should be noted that Champagne vines can resist temperatures of roughly -14 / -15 °C without any significant consequences.

SPRING FROSTS

When the buds sprout, young vine shoots are destroyed as soon as temperature falls below -2.5 °C. In Reims, frost risks after chardonnay budburst have increased despite the overall warming with 2.9 frosts against 2.1 for the reference period; that is a 38 % increase in frequency.

However, present statistics for spring frost damage show a rather moderate evolution from a 4.5 % crop loss to 5 %.

PRECIPITATIONS

Rainfalls seem to be only slightly affected by climate change.

In Epernay, the annual average has hardly moved, around 700 mm, close to the whole vineyard average

April to September rainfalls (333 mm) and the one of the maturation period (109 mm) haven't increased either.

Annual frequency of heavy rainfalls (above 20 mm over a single day) has not risen with 3.3 days over the past few years compared to 3.5 days over the reference period. This frequency over the April-September period follows the same trend (respectively 1.9 and 2.1 days).

However, over the maturation period, there is a slight increase with 0.9 day against 0.6 day. Storms can sometimes cause damages resulting from hail. Such damages, expressed annually in percentage of destroyed areas, are merely going from 1.6 to 1.7 %.

CLIMATE CHANGE IMPACT ON VINE PERFORMANCES

Climate change consequences on vine characteristics have appeared in Champagne since the late 80's. For the last 25 years, this evolution has been, from an agronomical point of view, positive.

The annual growth cycle of the vines is shorter. Flowering time is two weeks earlier and picking is three weeks earlier. The length between flowering and harvest is one week shorter.

Temperatures have increased while the monthly natural water supply has been regular. Consequently, grape quality and yield have improved in the same period. Potential alcohol content has grown by approximately

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1 % vol., while acidity has lost 2 g H_2SO_4/L. Yield increased 5 000 kg/ha though inputs like fertilization slipped.

GROWERS AND MERCHANTS (BRAND OWNERS) POINT OF VIEW

Climate change is both considered by growers and merchants as a very important challenge.

The main targets are focusing on technics to adapt vine practices and wine process and the strategy to mitigate climate change.

VINE ADAPTATIONS

Until today, traditional cultural practices are sufficient to adapt the management of Champagne vineyard.

Nevertheless, attention should be paid to emerging pathogens, or to their extension, with as a possible and negative consequence, some unexpected off-flavors in the wines.

To anticipate new evolutions, research is focusing on several topics such as the study of water in soils, new cultivars with longer cycle and less sensitivity to diseases, canopy management and new decision tools through precision viticulture.

Wine adaptations

Wines have been keeping the freshness and elegance which is the footprint of Champagne's style.

In addition to viticultural adjustments to climate change, blending, lower dosage and preventing malolactic fermentation are efficient tools for winemakers.

CHAMPAGNE STRATEGY TO MITIGATE CLIMATE CHANGE

Combating climate change requires both reducing greenhouse gas emissions (mitigation) and adopting strategies to adapt to climate change. Since 2003, the Champagne Committee (CIVC) has assessed the carbon footprint of Champagne, considering the all vineyard (34 000 ha) as a single company. Based on a previous environmental analysis, four major targets have been set. Energy and climate challenge is one of them. The aim is to reduce the greenhouse gas emissions by – 25 % by 2020 and -75 % by 2050. To reach this objective, sixteen R & D programs and forty actions are underway or planned.

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[1] Huglin index : it consists of a climatic index commonly used in wine-growing agrometeorology. Over the reference period, it gets near 1,600 degree-days in Champagne, 1,800 degree-days in the Bordeaux area, 2,100 degree-days in Montpellier, 2,300 degree-days in Perpignan.

THE EFFECT OF VITICULTURAL CLIMATE ON RED AND WHITE WINE TYPICITY

Characterization in Ibero-American grape-growing regions

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Abstract

Aim : This study is part of a CYTED (Ibero-American Program for Science, Technology and Development) project on vitivinicultural zoning. The objective was to characterize the effect of viticultural climate on red and white wine typicity in the macro Ibero-American viticultural region.

Methods and results : The climate of 46 grape-growing regions in 6 Ibero-American countries (Argentina, Bolivia, Brazil, Chile, Spain and Portugal) was characterized using the three viticultural climate index of the Geoviticulture MCC System : the Heliothermal index HI, the Cool Night index CI and the Dryness index DI. The main sensory characteristics frequently observed in representative red and white wines of each of these regions were described by enology experts in the respective countries : intensity of colour, aroma, aroma-ripe fruit, body-palate concentration, alcohol, tannins (for red wines) and acidity as well as persistence on the palate. The data were submitted to a correlation analysis of the variables and Principal Component Analysis (PCA).

Conclusion : The typicity of red and white wines was correlated with the HI, CI and DI viticultural climate indexes from the MCC System. The main wine sensory variables affected by viticultural climate were identified.

Significance and impact of the study : The results can be used to project the potential impacts of climate change on wine sensory characteristics.

Key words : Ibero-American grape-growing areas, viticultural climate indexes, wine typicity, sensory variables, climate change

Résumé

Objectif : Cette étude fait partie d'un projet CYTED (Programme Ibéro-Américain de Science et Technologie pour le Développement) sur le zonage vitivinicole. L'objectif a été de caractériser l'effet du climat viticole sur la typicité des vins rouges et blancs dans la macro région viticole Ibéro-Américaine.

Méthodes et résultats : Le climat de 46 régions viticoles situées dans 6 pays Ibéro-Américains (Argentine, Bolivie, Brésil, Chili, Espagne et Portugal) a été caractérisé par les trois indices climatiques viticoles du Système CCM Géoviticole : l'indice Héliothermique IH, l'indice de Fraîcheur des Nuits IF et l'indice de Sécheresse IS. Les caractéristiques sensorielles les plus fréquemment observées dans les vins rouges et blancs représentatifs de chacune des régions ont été évaluées par des œnologues experts de chaque pays : l'intensité de la couleur, de l'arôme, de l'arôme de fruit mûr, de la concentration, de l'alcool, des tanins (pour les vins rouges) et de l'acidité de même que la persistance.

Conclusion : Une corrélation entre la typicité des vins rouges et blancs et les indices climatiques viticoles IH, IF et IS du Système CCM a été mise en évidence. Les principales caractéristiques sensorielles du vin affectées par le climat viticole ont été identifiées.

Signification et importance de l'étude : Les résultats peuvent être utilisés pour tenter de donner une idée de l'impact du changement climatique sur les caractéristiques sensorielles des vins.

Mots clés : régions viticoles Ibéro-Américaines, indices climatiques viticoles, typicité des vins, variables sensorielles, changement climatique.

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INTRODUCTION

The effect of climate on grape composition and wine characteristics and typicity has been characterized in many specific viticultural regions and climates worldwide. However, few studies have characterized this effect at global scale considering different climates.

This study is part of a CYTED (Ibero-American Program for Science, Technology and Development) project on vitivinicultural zoning (CYTED, 2003 ; Sotés & Tonietto, 2004). The objective was to characterize the effect of viticultural climate on the typicity of red and white wines in the macro Ibero-American viticultural region, as perceived by expert enologists.

MATERIAL AND METHODS

1. Methodology

The methodology was applied to 46 main grape-growing regions across 6 Ibero-American countries: Argentina (Catania et al., 2007), Bolivia, Brazil, Chile, Spain and Portugal. The viticultural climate of each region was characterized using the three viticultural indexes of the Geoviticulture MCC System (Tonietto, 1999 ; Tonietto & Carbonneau, 2004): HI (Huglin's Heliothermal Index), CI (Cool Night Index) and DI (Dryness Index). The indices were calculated based on the inter-annual climate averages collected from a representative weather station in each region.

2. Sensory evaluation

The main sensory variables frequently observed in dry red and white wines (up to 12 months after alcoholic fermentation) produced from representative grape(s) of each of the 46 grape-growing regions were described (based on empirical knowledge) by experienced enologists in the respective countries using the methodology of Zanus & Tonietto (2007). The sensory evaluation concerned the intensity of wine descriptors most affected by viticultural climate: Colour (Cou), Aroma - Intensity (Ar), Aroma - Ripe Fruit (Ar-Fm), Concentration (Con), Alcohol (Al), Tannins (Tan; only for red wines), and Acidity (Ac). Persistence (Per) on the palate was also evaluated. The experts used a sensory evaluation form consisting of a 5-point intensity scale where 1 = low intensity and 5 = high intensity (Table 1).

3. Data analysis

The variable set was submitted to a correlation analysis and Principal Component Analysis (PCA).

RESULTS AND DISCUSSION

1. Red wines

The average and standard deviation of viticultural climate indices and wine sensory variables across the 46 grape-growing regions are shown in Table 2. The average HI value was 2.411, with a minimum of 1.710 and a maximum of 3.572; the average CI value was 13.3 °C, with a minimum of 8.1 °C and a maximum of 21.7 °C; and the average DI value was -68 mm, with a minimum of -276 mm and a maximum of 200 mm. This is a good representation of the variability observed at global scale, except in very cool and cool climates. The averages for all sensory variables ranged from 3.0 (Ac) to 3.7 (Al, Ar-Fm, and Cou) and standard deviations from 0.66 (Al) to 0.83 (Cou).

Table 3 shows the correlation coefficients between MCC System climate indices and sensory variables for all 46 grape-growing regions. The following significant correlations were found: HI - positive correlation with Al and negative correlation with Ac; CI - negative correlation with Cou, Ar, Con, Tan and Per; and DI - positive correlation with Ac and negative correlation with Al.

The correlations between climate indices and red wine sensory variables were analyzed using PCA analysis

Table 1. Sensory evaluation form of red and white wines from different grape-growing regions.

Sensory Descriptor	Low		Intensity Trend →		High
Colour - Intensity					
Aroma - Intensity					
Aroma – Ripe fruit - intensity					
Concentration - intensity					
Alcohol - intensity					
Tannins – intensity (red wines)					
Acidity - intensity					
Persistence					

(Figure 1, left plot). The first two principal components (PC1 and PC2) accounted for 63.21 % of the variability.

This analysis strengthen the correlation results reported in Table 3 and confirms the effect of temperature (HI) on the increased perception of Alcohol and the decreased perception of Acidity in red wines. With respect to soil water supply, the highest DI values contributed to the increased perception of Acidity and the decreased perception of Alcohol. The analysis also highlights the effect of night temperature at ripening time on wine sensory characteristics : cool nights (lowest CI values) contributed to the increased perception of Colour, Tannins, Aroma, Concentration and Persistence.

2. White wines

The average and standard deviation of viticultural climate indices and wine sensory variables across the 46 grape-growing regions are shown in Table 2. The average HI value was 2.411, with a minimum of 1.710 and a maximum of 3.572 ; the average CI value was 13.5 °C, with a minimum of 8.1 °C and a maximum of 21.7 °C ; and the average DI value was -53 mm, with a minimum of -276 mm and a maximum of 200 mm. Again, this is a good representation of the variability observed at global scale, except in very cool and cool climates. The averages for all sensory variables ranged from 2.4 (Cou) to 3.6 (Al) and standard deviations from 0.65 (Cou and Al) to 0.99 (Ar-Fm).

Table 3 shows the correlation coefficients between MCC System climate indices and sensory variables for all 46 grape-growing regions. The following significant correlations were found : HI - positive correlation with Al and negative correlation with Ac ; CI - positive correlation with Cou and negative correlation with Ar, Ar-Fm, Ac and Per ; and DI - positive correlation with Ac and Cou.

The PCA analysis of the correlations between climate indices and white wine sensory variables is depicted in Figure 1 (right plot). The first two principal components (PC1 and PC2) accounted for 60.45 % of the variability. The third principal component (not shown) accounted for 17.45 % of the variability and highlighted the « DI x Cou » clustering.

This analysis strengthen the correlation results reported in Table 3. With respect to temperature, the results for white wines follow the same trend as that for red wines, that is, an effect of HI on the increased perception of Alcohol and the decreased perception of Acidity. The analysis also highlights the effect of night temperature at ripening time on wine sensory characteristics : cool nights (lowest CI values) contributed to the increased perception of Aroma (Ar

Table 2. Average and standard deviation in MCC System climate indices and wine sensory variables for all 46 grape-growing regions under study

Wines		HI	CI	DI	Cou	Ar	Ar-Fm	Con	Al	Tan	Ac	Per
Red	Average	2411	13.3	-68	3.7	3.6	3.7	3.6	3.7	3.4	3.0	3.6
	Standard deviation	399. 03	2.99	120.47	0.83	0.71	0.71	0.75	0.66	0.72	0.80	0.71
White	Average	2411.4	13.5	-53	2.4	3.5	3.2	2.9	3.6	-	2.8	3.3
	Standard deviation	400.41	3.01	128.24	0.65	0.96	0.99	0.95	0.65	-	0.79	0.86

Table 3. Correlation coefficients between climate indices of the MCC System and wine sensory variables for all 46 grape-growing regions under study : red wines (in red) and white wines (in green)

Variable	HI	CI	DI	Cou	Ar	Ar-Fm	Con	Al	Tan	Ac	Per
HI	1.00	0.59**	-0.39**	0.11	-0.15	-0.13	0.16	0.34*	-	-0.63**	-0.28
CI	0.60**	1.00	0.03	0.36*	-0.31*	-0.37*	-0.12	0.25	-	-0.39**	-0.42**
DI	-0.35*	0.06	1.00	0.42**	-0.01	-0.09	0.08	-0.15	-	0.58**	0.05
Cou	-0.25	-0.45**	0.05	1.00	-0.01	-0.13	0.22	0.54**	-	-0.05	0.00
Ar	0.08	-0.33*	-0.15	0.41**	1.00	0.86**	0.62**	0.05	-	0.31*	0.73**
Ar-Fm	0.10	-0.20	-0.25	0.40**	0.65**	1.00	0.68**	-0.03	-	0.30*	0.78**
Con	-0.13	-0.34*	-0.04	0.72**	0.51**	0.55**	1.00	0.45**	-	0.15	0.58**
Al	0.36*	0.09	-0.49**	0.12	0.21	0.39**	0.31*	1.00	-	-0.38**	0.02
Tan	-0.21	-0.35*	0.12	0.76**	0.24	0.25	0.67**	-0.01	1.00	-	-
Ac	-0.55**	-0.25	0.53**	0.37*	-0.22	-0.06	0.31*	-0.45**	0.49**	1.00	0.42**
Per	-0.14	-0.41**	-0.21	0.56**	0.74**	0.65**	0.59**	0.31*	0.37*	-0.02	1.00

In bold are significant correlations at the 0.05 (*) and 0.01 (**) probability level

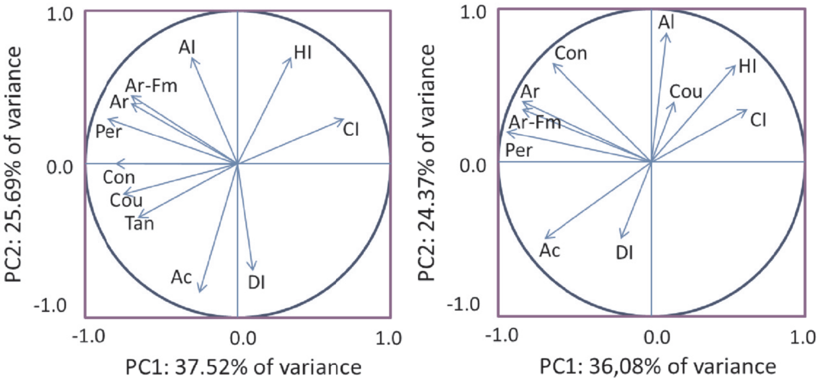

Figure 1. Principal Component Analysis (PCA) of MCC System climate indices (HI, CI and DI) and sensory characteristics (Cou, Ar, Ar-Fm, Al, Con, Tan, Ac and Per) of red (left plot) and white wines (right plot) for all 46 grape-growing regions under study.

and Ar-Fm), Acidity and Persistence and the decreased intensity of Colour. Finally, the highest DI values contributed to the increased perception of Acidity and Colour. The correlation between high colour intensity and high DI (wetter areas) observed in white wines may be attributed to a faster evolution of colour, given that these wines usually have lower alcohol levels.

3. Climate change and wine typicity : relationship between wine sensory patterns and MCC climate indices

This study across Ibero-American grape-growing regions can provide insights into the impact of climate change (and hence changes in MCC climate indices) on wine sensory patterns.

Considering that climate change will lead to warmer temperatures, HI is likely to increase. The same is true for minimum temperatures, which means that CI is also likely to increase in the future. Climate change may also lead to greater variability in rainfall across viticultural areas, which may result in lower DI in certain areas (if considering the atmospheric demand in response to increasing temperature). Figure 2 shows the main trends in sensory perception for red and white wines according to future climate change scenarios and associated changes in MCC System climate indices (based on the significant correlations presented in Table 3, considering an increase in HI and CI and a decrease in DI).

CONCLUSIONS AND CONSIDERATIONS

This study shows that wine typicity is determined in part by the regional viticultural climate and that the MCC System viticulture indices are significantly related to wine sensory characteristics.

The response of wine sensory characteristics to both viticultural climate and climate change is, of course,

Sensory descriptor	MCC Climate index		
	HI ↗	CI ↗	DI ↘
Colour - intensity		↗↘	↘
Aroma - intensity		↘↘	
Aroma - Ripe fruit - intensity		↘	
Concentration - intensity		↘	
Alcohol - intensity	↗↗		↗
Tannins - intensity (red wines)		↘	
Acidity - intensity	↘↘	↘	↘↘
Persistence		↘↘	

Figure 2. Potential trends in sensory perception for red (in red) and white wines (in green) in response to climate change, considering an increase in HI and CI and a decrease in DI (and vice versa for < HI, < CI and > DI).

not linear. It is also influenced by numerous factors, such as grape variety and its interactions with the environment and the cultural and enological practices of each region.

Nevertheless, the results obtained in this study, and future studies using the same methodology, could be used in wine typicity projections for potential grape-growing regions and in the qualitative assessment of wine typicity in response to climate change for current grape-growing regions.

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A MULTI-SCALE CLIMATIC ANALYSIS OF VITICULTURAL TERROIRS IN THE CONTEXT OF CLIMATE CHANGE : THE "TERADCLIM" PROJECT

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Abstract

This article presents the "ANR-TERVICLIM" research programme, which was taken over by the "GICC-TERADCLIM" project, aiming at observing climate at local scales in different wine producing regions worldwide and simulating both climate and climate change at fine scales in order to produce a fine scale assessment of climate change impacts. The end goal is to simulate adaptation scenarios for viticulture, providing guidance to decision-makers in the viticultural sector. Examples are given for various viticultural terroirs to illustrate the multi-scale climatic approach.

Key words : multi-scale, fine scale, spatial climatic variability, viticultural terroir, climate change

Résumé

Cet article présente les programmes de recherche "ANR-JCTERVICLIM" et "GICC-TERADCLIM" sur l'observation et la modélisation spatiale du climat à l'échelle des terroirs viticoles dans le contexte du changement climatique. L'originalité de ces programmes concerne la mise en place de réseaux de mesures agroclimatiques dans des vignobles répartis dans de nombreuses régions viticoles du monde. La méthodologie consiste à réaliser des mesures agroclimatiques à l'échelle des terroirs viticoles étudiés puis de modéliser les climats locaux. L'objectif final est de simuler le climat et le changement climatique à des échelles spatiales fines afin de produire des scénarios du changement climatique adaptés aux terroirs viticoles, fournissant des informations en support aux prises de décision dans le secteur viticole. Des exemples sur différents terroirs viticoles mondiaux sont exposés montrant l'approche multi-échelle du climat et du changement climatique.

Mots clés : multi-échelle, échelle fine, variabilité climatique spatiale, terroir viticole, changement climatique

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INTRODUCTION

Climatic change is a global issue (Intergovernmental Panel on Climate Change - IPCC, 2007), however, the main effects and regional impacts are still to come (Le Treut, 2009 and 2010).

Awareness of climate change issues related to viticulture slowly grew in the 1990s (Kenny and Harrison, 1992; Bindi *et al.*, 1996). At that time, Bonnardot (1996) showed that a significant shortening of the period between flowering and harvest for the Pinot Noir cultivar in Burgundy could be associated with a significant increase in the August maximum temperature. The topic received increasing attention in the 2000s with studies showing the effect of increasing carbon dioxide on grapevine (Schultz, 2000; Bindi *et al.*, 2001). In recent years, the impact of climate change on grapevine phenological stages as well as on wine characteristics and quality has been intensively studied in most wine producing regions worldwide, showing the agroclimatic potential of different regions under changing climatic conditions (Chuine *et al.*, 2004; Duchêne and Schneider, 2005; Jones *et al.*, 2005; Garcia de Cortazar Atauri, 2006; Barbeau, 2007; Bois, 2007; Webb *et al.*, 2008; Bellia *et al.*, 2008; Bonnardot and Carey, 2008; Hall and Jones, 2010; Hunter *et al.*, 2010; Madelin *et al.*, 2010; Seguin, 2010; Neethling *et al.*, 2012; Bonnefoy *et al.*, 2013). The geography of viticulture could experience a 100-km extension/shift poleward in each hemisphere over the 2020-2050 period, leading to major adaptation issues (Vaudour, 2003; Malheiro *et al.*, 2010; Santos *et al.*, 2012). Since some regions are to benefit from climate change while others are likely to experience challenges for vine cultivation (Jones, 2006; Jones and Webb, 2010), adaptation methods will necessarily differ from region to region according to the degree of climate change experienced in the different regions (Schultz and Jones, 2010).

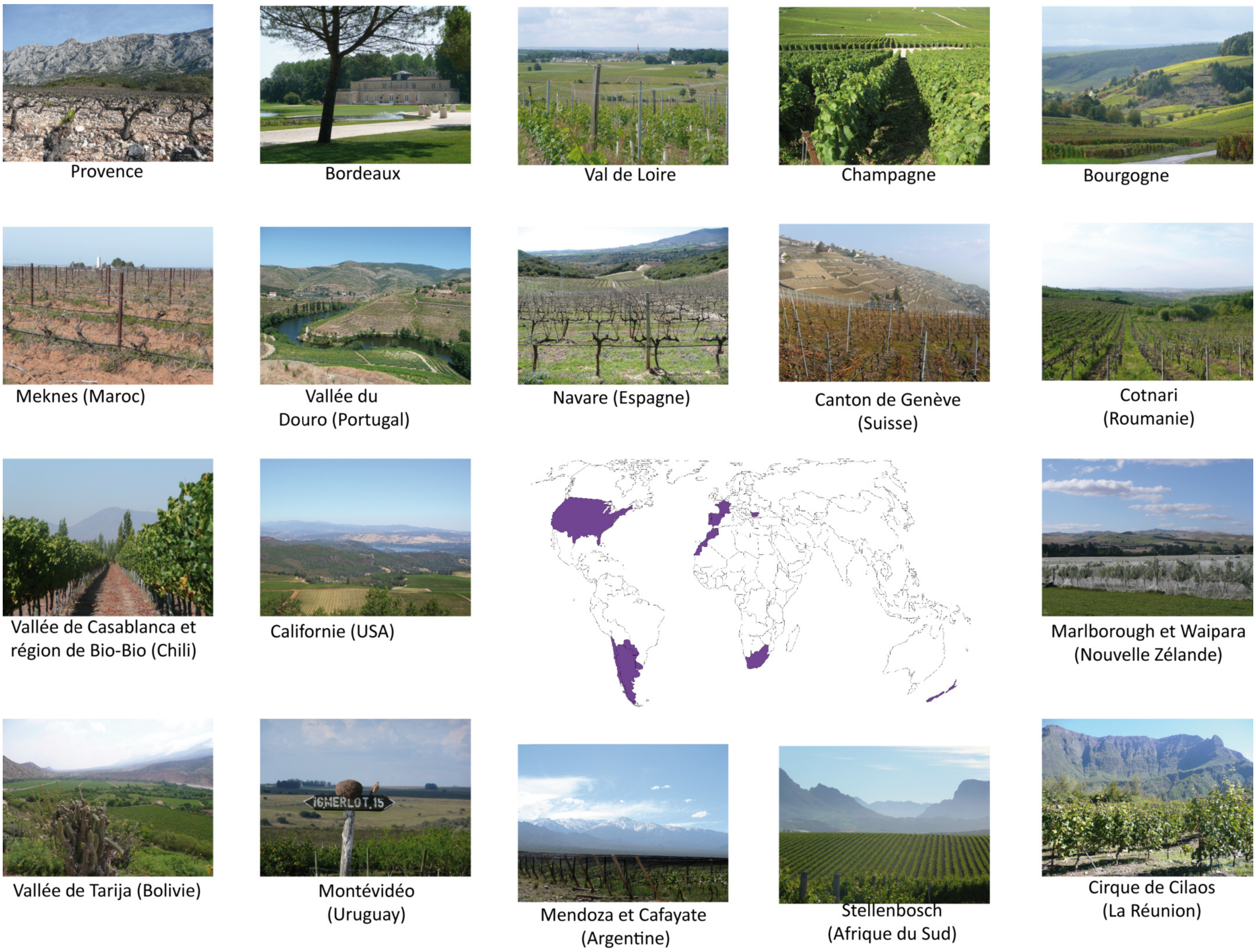


Figure 1 - TERVICLIM and TERADCLIM networks.

In order to assess the impact of climate change in a region, simulations of climate change are required to provide scenarios of future climate. The calculation of bioclimatic indices for the different IPCC SRES (Special Report on Emissions Scenarios) scenarios using the outputs of the HadCM3 global climate model (2.5° × 3.75° resolution) showed significant changes in the distribution of vineyards by 2070-2100 (Jones *et al.*, 2009; Malheiro *et al.*, 2010; Santos *et al.*, 2011). The use of the ARPEGE-Climat scenario (50-km resolution over France) and a generic crop model (the STICS - S*imulateur mulTIdisciplinaire pour les Cultures Standards* - crop model) applied to viticulture over the French wine producing regions provided a finer assessment of the regional impacts of climate change (Garcia de Cortazar Atauri, 2006). Tools to regionalize the scenarios derived from global models are now well developed (Pagé, 2008; Terray *et al.*, 2010) for application to various agro ecosystems including viticulture (Pieri, 2010). Statistical or dynamical downscaling (coarse to fine resolution) of climate information derived from global climate

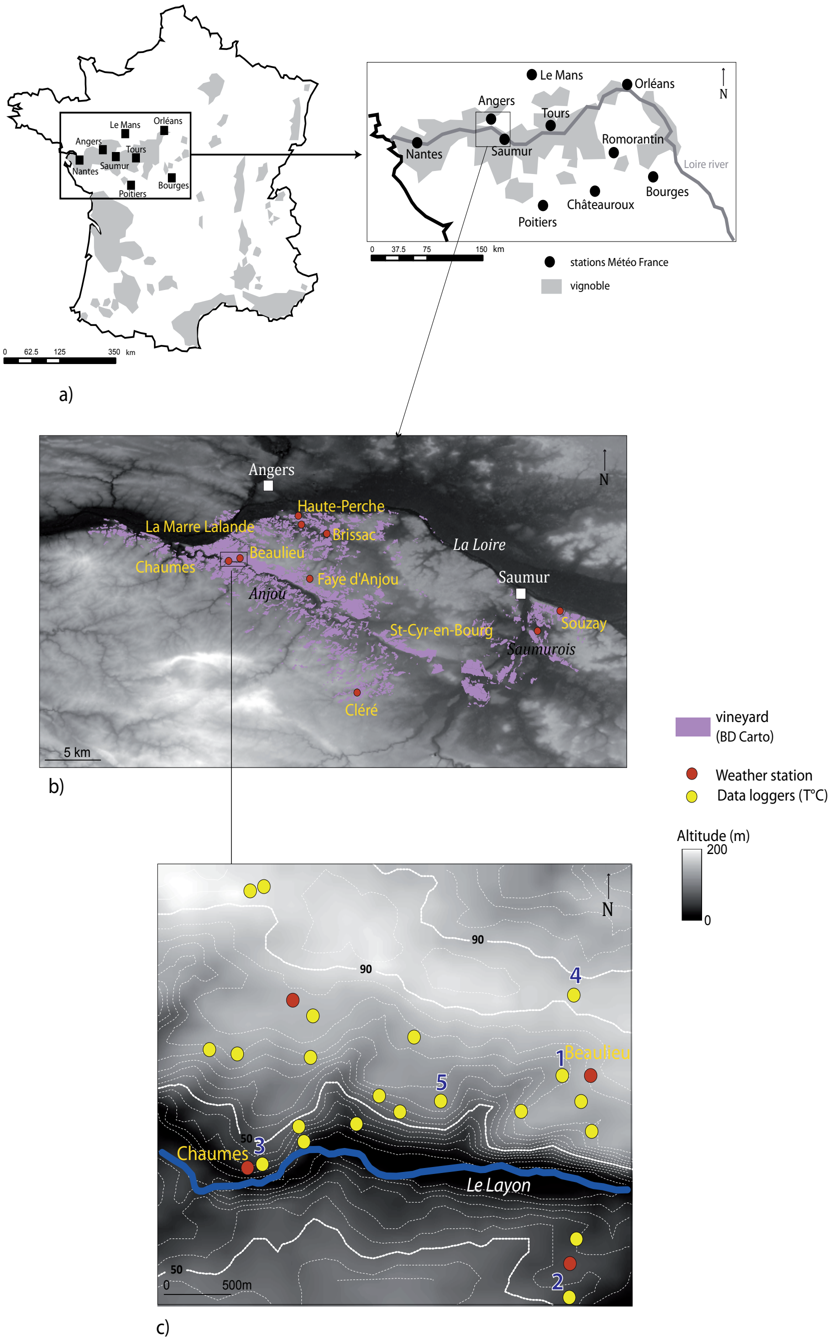


Figure 2 - Example of imbricated climatic networks in Loire Valley (France).

models is intensively used to develop information on climate change at local levels, where it is most needed by societies.

In the context of dealing with climate change issues at regional and local scales, the ANR-TERVICLIM and GICC-TERADCLIM research programmes are devoted to observing and simulating both climate and climate change at the viticultural "terroir" scale (i.e., at local scale) using a multi-scale climatic approach. Phenological variations as well as differences in grape/wine quality are often observed over short distances within a wine region and are related to local characteristics (slope, soil, seasonal climate, etc.). These local variations in the environment are specific to a given location and need to be investigated systematically in order to be considered in the context of a rational policy of viticultural adaptation to climate change at local scale.

Both research programmes are dedicated to (i) climate observation at local scales and grapevine monitoring in different wine producing regions worldwide and (ii) the simulation of both climate and climate change in order to produce a fine scale assessment of climate change impacts (as defined for New Zealand in Sturman *et al.*, 2011).

CLIMATIC OBSERVATIONS AT FINE SCALE AND GRAPEVINE MONITORING

The spatial resolution of national climate monitoring networks is often too coarse to provide a clear picture

Figure 3 - Temperature sensor (a) and Plant Cam (b).

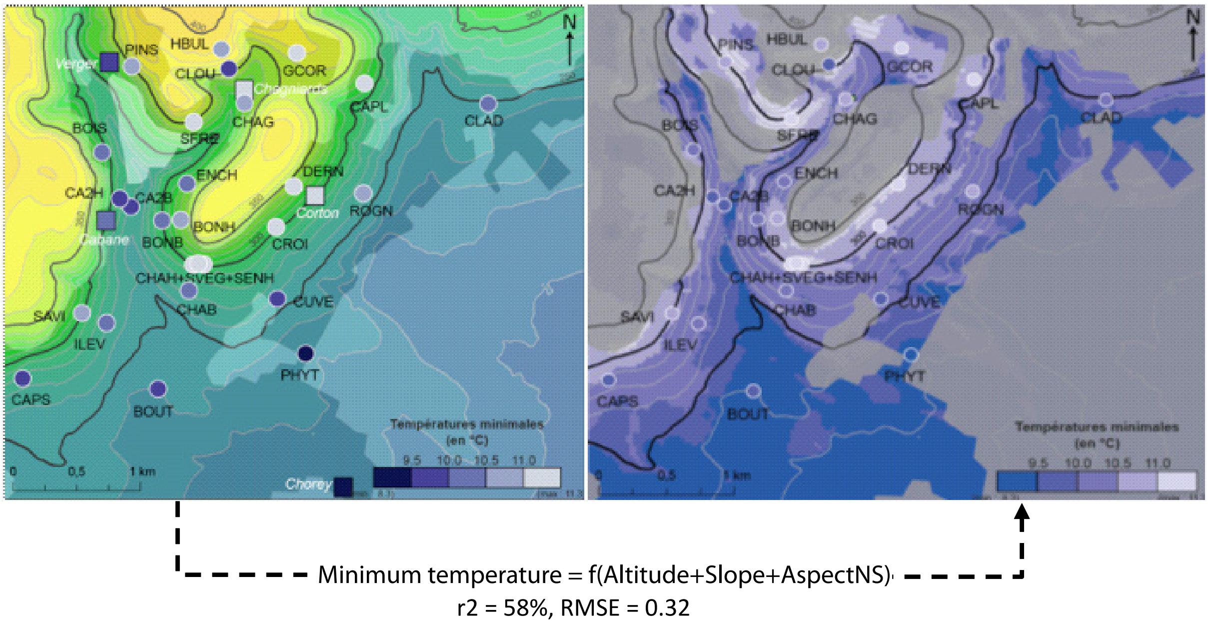
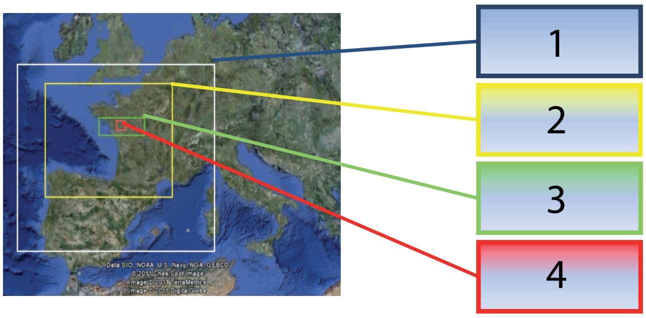
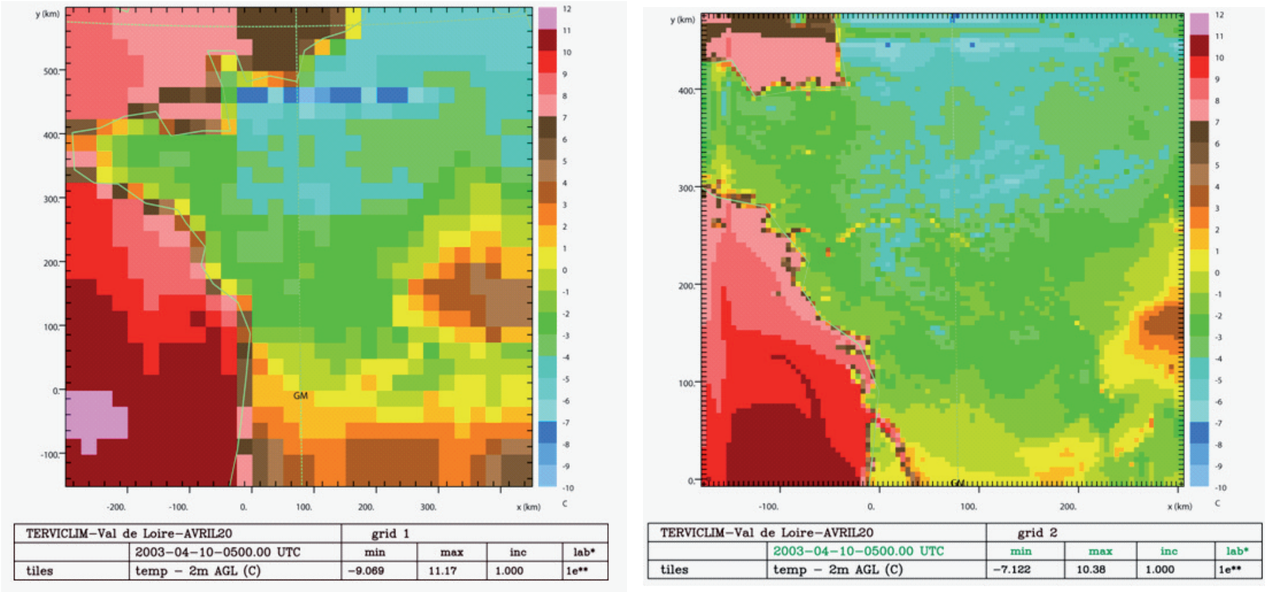
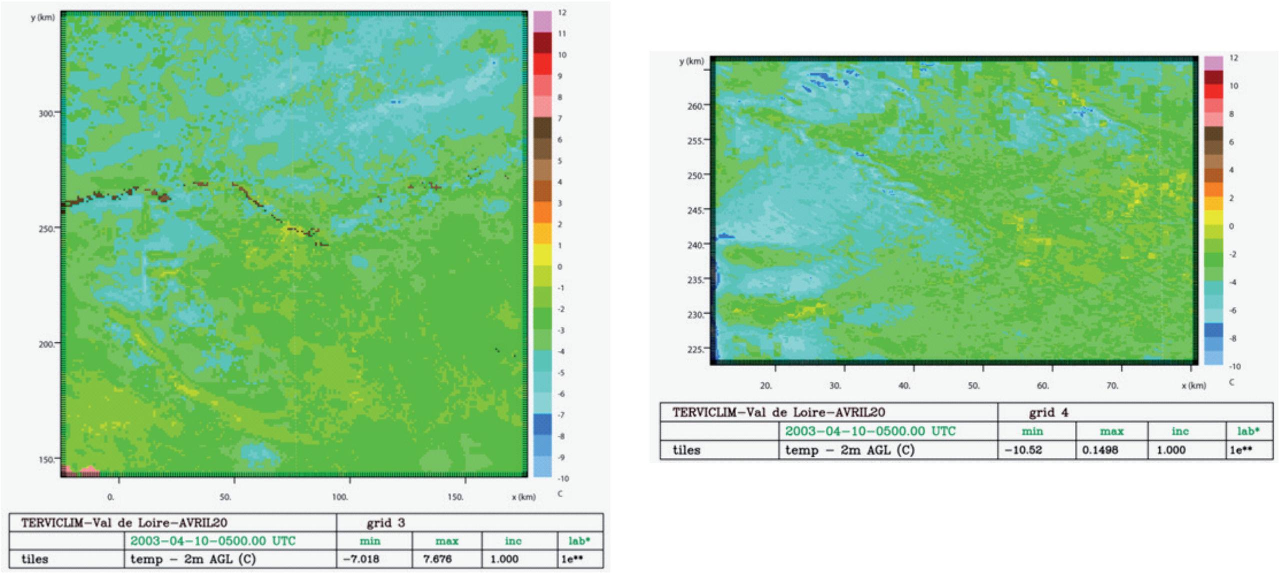


Figure 4 - Observed (a) and modeled (b) temperatures using multicriteria modeling: example of minimum temperatures for May 2011 in the Corton vineyards (Burgundy, France) (©Madelin).





a) Grid 1(25km) Grid 2 (5km)



b) Grid 3 (1km) Grid 4 (200m)

Figure 5 - Imbricated grids for meso-scale atmospheric modeling (a): example of the « Loire Valley » vineyard (b).

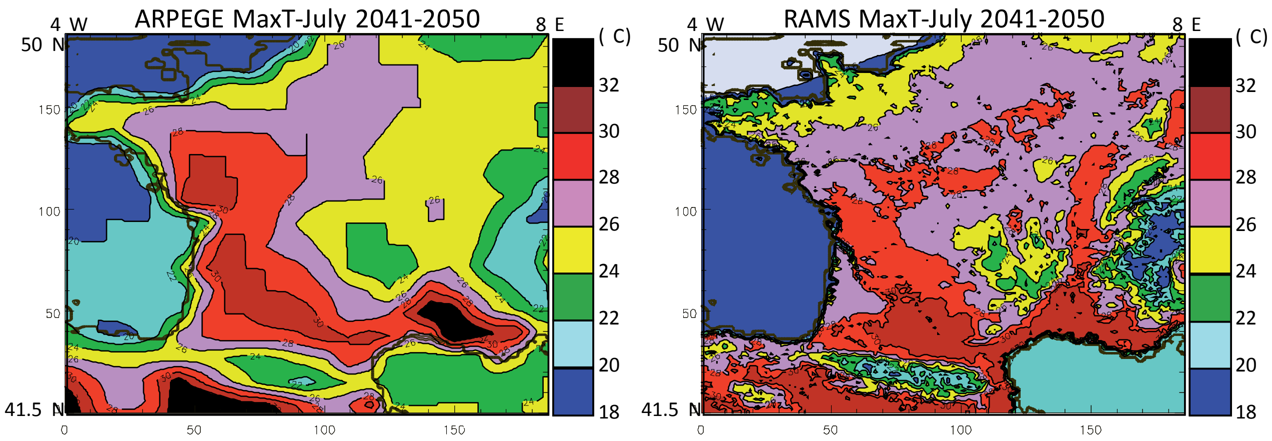


Figure 6 - Climate change modeling: dynamical downscaling of ARPEGE-Climat outputs using a Regional Atmospheric Modeling System (RAMS). Example of simulated July Maximum Temperature for 2041-2050 under the SRES A2 conditions with (a) ARPEGE-Climat at 50-km resolution and (b) RAMS at 5-km resolution (In Bonnardot et al., 2012c).

of the temperature patterns in wine regions of complex terrain. The originality of the programmes lies in a unique network of thermal sensors and weather stations established since 2008 (Figure 1). The network consists of 400 thermal sensors located in more than 20 wine estates in 13 wine producing countries. This fine scale network provides valuable data to assess the spatial variability in each site, perform multicriteria spatial modeling, and validate numerical simulations (Bonnardot *et al.*, 2012a). Each experimental site consists of an imbricated network of climate monitoring (Figure 2).

Tinytag data loggers (Gemini, Tinytag Talk 2, TK-4023) set inside a ACS-5050 Stevenson type screen set mounted on a trellis pole in a grapevine row represent the finest level of climate monitoring (Figure 3a). The choice of the locations for the data loggers depends on topography (need to represent all aspects, altitude, etc.) and soils (need to represent the differences in soil characteristics) and their number depends on the environment (diverse or not) and the estate/area surface (need to cover regularly the considered estate/area to help in the spatial mapping via multicriteria modeling). Standardization between loggers is ensured in the best possible way (e.g., removal of canopy growth around loggers) to prevent any data alteration. Weather stations are installed in the same area as the data loggers. They allow the analysis of local climatic conditions (e.g., wind speed and direction, humidity, precipitation, etc.) in relation to the spatial variability of temperature.

Grapevine growth is monitored in parallel in many of these sites to study the vine response to climate over short distances. Monitoring of grapevine consists of observations of phenological stages (occurrence of budburst, flowering, veraison and maturity) according to standard protocols or using plant cameras (Figure 3b), which capture images of leaves/berries at regular intervals (Neethling *et al.*, 2012).

CLIMATE MODELING AT FINE SCALE

Climate modeling at fine scale includes (1) the spatial modeling of climatic data from the fine scale measurement networks using multicriteria modeling at very high resolution (90 m), (2) the spatial and temporal modeling of weather events using meso-scale atmospheric modeling at 1-km to 200-m horizontal resolution and (3) future climate simulations using meso-scale climatic model ran under different climate change scenarios and using a 5-km horizontal resolution.

1. Multicriteria modeling

The role of topographic factors in the spatial variability of temperature at fine scales in addition to the influence of geographical location (latitude/longitude) at larger scale has been demonstrated. In order to construct fine scale spatial temperature fields, the multicriteria modeling approach, which takes these environmental factors into account, is used. Multivariate (stepwise) linear regressions are performed to explain the variability of the climatic data recorded by the data loggers, retaining as relevant priori factors: position (determined by GPS), altitude, slope and aspect, which are computed from this dataset using GIS software (Madelin and Beltrando, 2005). Indeed, this type of modeling makes use of climatic data provided by the fine scale network and spatial variability of temperature is provided at the fine scale resolution of 90 m. An example of spatial variability in terms of minimum temperature for May 2011 in “La Montagne de Corton” (statistically correlated to topographic parameters : slope, altitude) is displayed in Figure 4.

2. Meso-scale atmospheric modeling

Meso-scale atmospheric modeling is used to provide knowledge and understanding of the local physical atmospheric processes that cause climate variability in the different studied wine regions (Carey and Bonnardot, 2004 ; Bonnardot *et al.*, 2005 ; Bonnardot and Cautenet, 2009).

Numerical simulations of weather events were performed using regional climate models such as RAMS (Regional Atmospheric Modeling System) (Figure 5). They are both regional and non-hydrostatic models, based on the physical equations that govern the processes operating in the atmosphere, taking surface information (such as land cover, soil moisture and temperature) and large-scale atmospheric data (ECMWF (European Centre for Medium-Range Weather Forecasts) and NCEP (National Centres for Environmental Prediction) FNL (Final) Operational Global Analysis data) into account (Giorgi and Marinucci 1992 ; Machenhauer *et al.*, 2001 ; Sanchez *et al.*, 2004).

A series of nested grids (Figure 5) are used to reduce computational costs, while at the same time providing sufficient spatial resolution (Cotton *et al.*, 2003). Implementation of the regional models consisted of four domains over the wine producing regions : the coarser grid (25 km) was the computer domain and the forcing area for large-scale atmospheric circulations and the inner most grid translated local and regional circulations (200 m) (Bonnardot *et al.*, 2011 ; Briche *et al.*, 2011 ; Bonnardot *et al.*, 2012b). Climatic data from automatic weather station networks were used to validate the modeled outputs.

In order to assess climate change at regional scales, RAMS was initialized with a nudging at the lateral boundaries using the 3-D fields of a Global Model as described above. Two grids were used : the coarse Grid 1 with a 25-km horizontal resolution was principally devoted to synoptic circulations (large-scale forcing) and Grid 2 represented local circulations.

3. Climate change modeling

Outputs from the ARPEGE-Climat model of Météo-France, one of the climate models used by the IPCC (2007) for the projections of possible future climate change, could be used as large-scale forcing in a regional climate model. ARPEGE-Climat correctly reproduces the main features of European climate (Déqué *et al.*, 2007) and has been used to assess climate change impacts in France (Brisson and Levrault, 2010 (Green Book)). The horizontal spatial resolution of about 50 km is the best resolution so far to make climate change projections over the French wine producing regions and its hourly and daily datasets allow more precise studies applied to viticulture.

In order to assess climate change at finer regional scales, the outputs of ARPEGE-Climat were dynamically downscaled using RAMS and nested grids, providing downscaled datasets of 5-km horizontal resolution over France (Bonnardot *et al.*, 2012b and c). Simulations were performed for two periods : 1991-2000, to assess the method against observations and quantify the large-scale induced biases, and 2041-2050, as near future climate projection under the SRES A2 scenario conditions (Figure 6). RAMS contributed to deliver high resolution downscaled datasets for recent past (1991-2000) and near future (2041-2050) climates. Results showed the contribution of RAMS for assessing the potential impacts of climate change in some viticultural regions of France (at 5-km resolution) under the SRES A2 scenarios for the 2041-2050 period. Global climate scenarios produced by CERFACS (*Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique*) and Météo-France have achieved a spatial resolution of 8 km (DRIAS project) over France using statistical downscaling methods (Pagé, 2008). A comparison between the two models will be made to analyze the differences between the regional numerical simulations and statistical modeling.

CONCLUSION AND PERSPECTIVES

A longer time series from the fine scale climatic networks (in operation since 2008 for the oldest) will help to provide significant datasets for multicriteria modeling, which in turn will lead to a detailed mapping of climatic variability at fine scales. Fine scale climate variability along with grapevine monitoring will provide valuable information at the scale of viticultural terroirs.

Meso-scale atmospheric modeling is a powerful tool to get a better understanding of the physical processes operating in the atmosphere. Such numerical simulations are expected to be performed over each study domain.

Statistical downscaling of the high resolution dynamically downscaled datasets (5 km) is in progress as an attempt to provide a detailed assessment of future climate resources at the viticultural local scales even though we know this intermediary step may add uncertainties to the projections.

The high resolution information concerning a near future period is of greater interest for decision-makers in the agricultural sectors.

Further investigations including the analyses of (i) other climatic parameters (humidity and radiation), (ii) extreme minimum and maximum temperatures, as well as (iii) a larger number of weather stations within the different wine regions will improve the regional assessment of future climate risks.

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MODELLING THE FUTURE IMPACTS OF CLIMATE CHANGE ON FRENCH VINEYARDS

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Abstract

Aims: Significant impacts of climate change have already been observed in viticulture. The likely evolutions of CO_2 atmospheric concentration, temperature and rainfall could thoroughly modify vine phenology and physiology, water status and grape maturation. The purpose of this study was to use an ecophysiological model to predict these impacts for near and distant future.

Methods and results: Regionalized outputs of global climate models were used as inputs for an ecophysiological model simulating vine phenology and soil water balance. It was applied at five locations in France, with continuous simulations at a daily time step from 1950 to 2100. The uncertainties were estimated by comparing three different downscaling methods, all assuming an A1B scenario (~RCP6). From a limited set of parameter values, the sensitivity of the predicted impacts to vine variety, planting density and soil water holding capacity was also estimated.
The main predicted impacts were: 1) a phenology 20 to 40 days earlier; 2) a weak worsening in vine water status before harvest, easily managed by controlled deficit irrigation or planting density; 3) a decline in water drainage to depth, a likely long-term issue for aquifers; and 4) a temperature rise of 5°C or more during the veraison-maturation period, a consequence of earlier phenology combined with warmer atmosphere.

Conclusion: A critical rise of temperature during fruit ripening seems unavoidable, even for late-maturing varieties. Therefore, detrimental effects on grape phenolics and aromas could challenge quality in French viticulture.

Significance and impact of study: Modeling provides the means to anticipate climate change impacts and develop guidelines for new practices and viticulture adaptation.

Keywords: grapevine, climate change, adaptation, modeling

Résumé

Objectifs : Des impacts significatifs du changement climatique sur la viticulture ont déjà été observés. Les évolutions probables de la concentration en CO_2 de l'atmosphère, de la température et des précipitations devraient modifier profondément la phénologie et la physiologie de la vigne, son statut hydrique et la maturation du raisin. L'objet de cette étude était d'utiliser un modèle écophysiologique pour prédire ces impacts pour les futurs proche et lointain.

Méthodes et résultats : Des sorties régionalisées d'un modèle climatique global ont été utilisées comme entrées pour un modèle écophysiologique simulant la phénologie de la vigne et le bilan hydrique du sol. Cela a été appliqué à 5 sites en France, avec des simulations continues à un pas de temps journalier de 1950 à 2100. Les incertitudes ont été estimées en comparant trois méthodes de régionalisation différentes, toutes basées sur le scenario A1B (~RCP6). La sensibilité des impacts prédits au cépage, à la densité de plantation et à la réserve utile du sol a également été estimée en comparant un nombre limité de valeurs de ces paramètres.
Les principaux impacts prévus sont : 1) une avancée de la phénologie de 20 à 40 jours ; 2) une faible dégradation du statut hydrique de la vigne avant vendanges, facilement compensée par une irrigation contrôlée ou par une adaptation de la densité ; 3) une diminution du drainage d'eau en profondeur, probablement un problème à long terme pour les nappes ; et 4) une augmentation de température pendant la période véraison - maturation de 5°C ou plus, conséquence de la combinaison de l'avancée de la phénologie et du réchauffement de l'atmosphère.

Conclusion : Le réchauffement très important pendant la période de maturation semble inévitable, même avec un cépage tardif. Des effets néfastes sur les composés phénoliques et les aromes pourraient donc menacer la qualité de la viticulture française.

Importance et impact de l'étude : L'approche de modélisation permet d'anticiper les impacts potentiels du changement climatique et d'orienter de nouvelles pratiques et l'adaptation de la viticulture.

Mots-clés : vigne, changement climatique, adaptation, modélisation

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INTRODUCTION

Climate change has already had well known effects and is very likely to carry on in the near and more distant future (IPCC's Fourth Assessment Report (AR4) "Climate Change 2007" (IPCC, 2007) and early proofs of AR5). The main predicted evolutions in atmospheric variables are a continuous rise in CO_2 concentration, an increase in near ground temperatures and a modified precipitation pattern in relation to both rainfall quantity and dynamics. Plant functioning and agriculture outputs are to a large extent sensitive to these factors and therefore agricultural products are vulnerable to climate change.

For vineyards and wine production, some distinctive traits of the agronomic system may contribute to greater potential impacts of climate change. Above all, grape- and wine-growing is very sensitive to year-to-year climate variation, as evidenced by the vintage effect and the adaptation of different vine varieties to temperature gradients. Additionally, a large part of the grapevine growth cycle takes place during summer, a period when rising temperatures and modified rainfall regime are likely to have noticeable consequences (Schultz, 2000; Jones *et al.*, 2005; Schultz and Stoll, 2010). Moreover, the maturation thermal conditions significantly influence grape berry composition (Downey *et al.*, 2006; Duchêne *et al.*, 2010; Keller, 2010; Schultz and Stoll, 2010; Dai *et al.*, 2011) and therefore quality, while the harvest typically occurs well after summer maximum temperatures, in a transition period that is likely to undergo higher temperatures and modified rainfall regimes. Furthermore, as a perennial fruit crop, grapevine could be sensitive to long-term cumulative effects on vegetative cycle duration and whole plant carbon reserves management as well as to modified winter conditions influencing dormancy and phenology (Schultz and Stoll, 2010).

Current observations confirm that climate change has already had a significant impact on vineyards. On the one hand, climate warming (1) accelerated phenology and sugar accumulation, leading to higher alcohol content in wine, (2) induced a delay between technological (sugar, organic acids) and phenolic maturity, a concern for harvest decision and wine equilibrium, and (3) induced a loss of aromas and aroma precursors in berries, again due to an early maturation and therefore to a maturation occurring during a warmer period (Schultz, 2000; Jones and Davis, 2000; Duchêne and Schneider, 2005; Jones *et al.*, 2005; García de Cortazar Atauri, 2006; Schultz and Jones, 2010; Schultz and Stoll, 2010).

On the other hand, climate change could also have some positive effects on grapevine cultivation. As other C3 plants, grapevine photosynthetic activity will benefit from the increase in CO_2 concentration and an improvement in the water use efficiency (WUE) may be expected (Schultz and Stoll, 2010). In regular vineyards, the row-structured canopy and the relatively low leaf area index (LAI) both contribute to limit evapotranspiration and hence vine water stress. Moreover, the root system of well-established vineyards is often deep. All these factors explain why grapevine is quite tolerant to water shortage and also why the impact of climate change is difficult to assess *a priori*. Moreover, grape and wine quality is generally improved by a mild water stress during the maturation period. The recently observed trend of more frequent better vintages in some places, like Bordeaux, was credited to this effect but is difficult to extrapolate without the help of sound water balance simulations.

Furthermore, predicting climate change impact may be decisive for viticulture since significant climate changes are expected over the crop cycle time scale (30 years or more). Moreover, vineyard establishment costs make up a large part of expenses and anticipating the changes would help maintain or improve economic and environmental sustainability. A systemic adaptation able to cope with climate change impacts could involve different combinations of the main interacting factors, such as climate, vine variety, soil, training system and techniques. Ecophysiological models are useful tools to take into account these complex interactions that could arise or shift in new conditions (Schultz and Lebon, 2005; Malheiro *et al.*, 2010; Pieri, 2010; Schultz and Stoll, 2010; Santos *et al.*, 2012; Moriondo *et al.*, 2013). Therefore, the purpose of this study was to assess the likely impacts of climate change on viticulture with the help of ecophysiological models and, additionally, to assess the sensitivity of these impacts to factors potentially relevant for systemic adaptation.

MATERIALS AND METHODS

1. Simulation models

The likely impacts of climate change on vineyards were assessed by coupling an agronomic model simulating phenology and soil water balance to regionalized outputs of global climate models. In order to assess, to some extent, the uncertainties associated with climate predictions, 3 different downscaling methods were compared. All simulations were performed on the basis of the same A1B scenario of greenhouse gas emission evolution, which is supposed to be realistic enough or at least not too extreme

(IPCC, 2007) and close to the forthcoming RCP6 scenario (early proofs of IPCC's AR5). The same global circulation model "Arpege" was used and its outputs regionalized according to 3 different downscaling methods: weather type (WT), quantile-quantile (QQ) and anomalies (ANO) (Terray *et al.*, 2010). The former two methods were considered more realistic since taking into account a spatial (WT) or statistical consistency (QQ) of climate data (Boé and Terray, 2008), whereas the latter (ANO) did not allow for changes of variance in the future.

2. Study sites and parameters

The study focused on 5 viticulture sites in France, representative of different production areas and different climates. The same biophysical model (Lebon *et al.*, 2003; Schultz and Lebon, 2005) was used to simulate vine phenology, vine water status and vineyard water balance. Daily simulations were performed by the model using daily series of the regionalized climate variables as inputs, from 1950 to 2100 without any reset at any time, therefore allowing cumulative effects to develop, especially on the soil water reserve reloading. All the simulations assumed a flat horizontal vineyard with no cover crop and with a row-structured canopy representing a vertical plane trellis system. The rows were parallel to the NS direction. Two water regimes were compared: rain fed and irrigated vines, where the irrigation was supposed to mimic an economical and efficient buried drip-irrigation system. The quantity of irrigation water applied was controlled according to a regulated deficit irrigation scheme defined by daily actual/maximum evapotranspiration ratio (ET/ETM) maintained at 0.3 or more. The sensitivity of the simulated impacts to the following parameters was also estimated: vine variety (Chardonnay, Merlot and Grenache, these varieties differing only in their earliness of phenology for the model), planting density (0.3 and 0.9 plants/m^2) and soil water holding capacity (fixed at 73, 150 and 226 mm, respectively) (Pieri, 2010).

3. Data

Most of the results presented here are expressed as annual means and standard deviations calculated over a period of 30 years. The study focused on 3 different periods representative of the 21st century climate evolution: recent past (RP) 1970-1999 (used as reference), near future (NF) 2020-2049 and distant future (DF) 2070-2099.

RESULTS

1. Climate inputs

All simulations were based on the A1B scenario (~RCP6). Therefore, well-known temperature rises of about 1.5°C and 3.0°C for near and distant future, respectively, were simulated, with little influence of the downscaling method (Fig. 1a). The predicted atmospheric warming was also very consistent between the different French sites investigated. However, the magnitude of this temperature rise is enough to induce deep changes in plant behavior, as already stated (Schultz, 2000; Jones and Davis, 2000; Duchêne and Schneider, 2005; Jones *et al.*, 2005; García de Cortazar Atauri, 2006; White *et al.*, 2006; Schultz and Stoll, 2010). On another hand, precipitation simulations exhibited not only a trend to

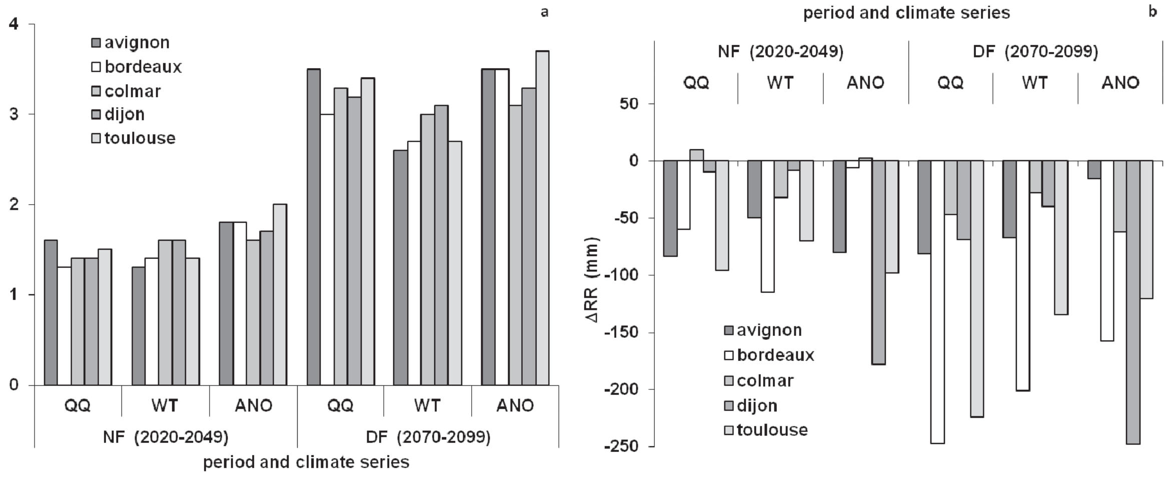

Figure 1 - Simulated variations of annual mean temperature (a) and rainfall (b) with reference to the 1970-1999 period at 5 wine-growing locations in France: Avignon, Bordeaux, Colmar, Dijon and Toulouse; means calculated over two 30-year periods, near future (NF) 2020-2049 and distant future (DF) 2070-2099, are compared to recent past (RP) 1970-1999; A1B (~RCP6) climate scenario; quantile-quantile (QQ), weather type (WT) and anomalies (ANO) downscaling methods.

dryer conditions but also a large spatial heterogeneity and large differences between the downscaling methods (Figure 1b). These variations reflect the larger uncertainties about precipitations, at a global scale as well as at the regional mid-latitude Europe scale (IPCC, 2007). Therefore, distinct impacts of precipitation change could be expected with regard to vineyard water balance, according to the location or the downscaling method.

2. Phenology

For the current wine-growing areas, the entire growth cycle will be brought forward by 20-40 days between RP and DF. As phenology is tightly linked to cumulative temperatures, a likely consequence of climate change is a shift of the different developmental stages towards earlier times (Figure 2). The main phenological stages are then expected to occur about 15 days and 30 days earlier in the near- and distant-future periods, respectively (Figure 2). With some minor differences, the same trend was observed whatever the vine variety or the downscaling method (results not shown). No change in variability was noticeable for the flowering date, whereas the full maturity stage exhibited a shift towards lower year-to-year variability (Figure 2). As a consequence of earlier maturity, some northern sites where a given variety did not reach maturity in recent past will become suitable for production or more consistent (Figure 2b). Therefore, a direct consequence of the advance in the phenology calendar will be a change in the feasibility of growing the crop in different places across the northern boundary of the cultivation area. The likely northward expansion of areas suitable for grape production is quite similar for different varieties and downscaling methods and confirms other studies (White *et al.*, 2006; Webb *et al.*, 2007; Malheiro *et al.*, 2010; Santos *et al.*, 2012; Hannah *et al.*, 2013; Moriondo *et al.*, 2013).

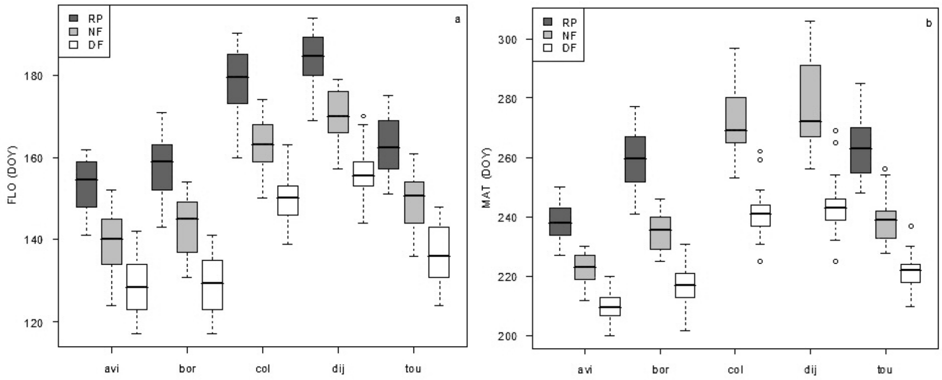

Figure 2 - Simulated flowering (a) and maturity (b) dates (DOY) at 5 wine-growing locations in France; boxplots with usual conventions representing 30-year periods: recent past (RP) 1970-1999, near future (NF) 2020-2049 and distant future (DF) 2070-2099; Merlot variety; A1B (~RCP6) climate scenario; WT downscaling method [RP maturity is missing in Colmar and Dijon because Merlot did not reach maturity consistently].

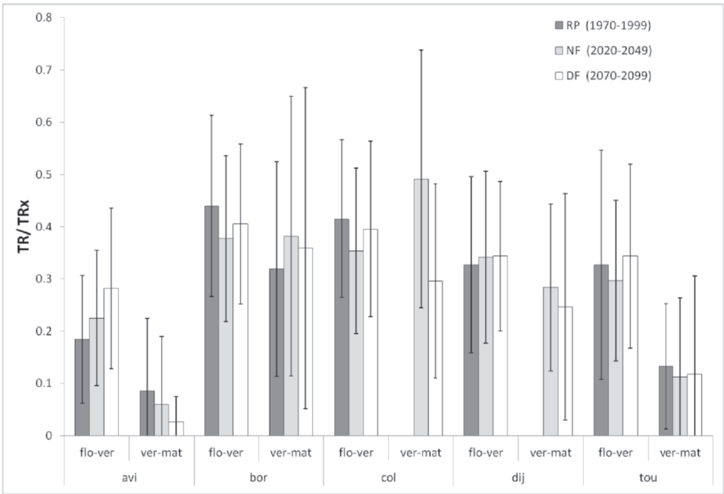

Figure 3 -Simulated vine actual/maximum transpiration ratio averaged over the flowering-veraison (flo-ver) and veraison-maturity (ver-mat) periods at 5 wine-growing locations in France; means over 30-year periods ± standard deviations; Merlot variety; A1B (~RCP6) climate scenario; WT downscaling method; rain fed vines; 73 mm soil water holding capacity; 0.9 plants/m² density. [RP TR/TRx ver-mat is missing in Colmar and Dijon because Merlot did not reach maturity consistently].

3. Vine water status

The likely evolution of water status was investigated by comparing the mean vine actual/maximum transpiration ratio (TR/TRx) calculated by the model and averaged over two periods, from flowering to veraison and from veraison to maturity (Figure 3). This ratio was computed according to soil water depletion during the same periods and thus results from long-term cumulative effects of rainfall and evapotranspiration dynamics. Despite a general increase in climatic water deficit due mainly to reduced rainfall (Figure 1), the water status of the vines was mostly maintained at the same level (Figure 3). However, few sites exhibited a decrease in TR/TRx during the veraison-maturity period: Avignon and Colmar, two sites where the climatic water balance (P-ET0) was already negative in the recent past. It may be assumed that the shortening of the cycle and the advance of these phenological stages towards relatively more rainy periods counteracted the reduction of available water in summer or that other components of the water balance were involved in the

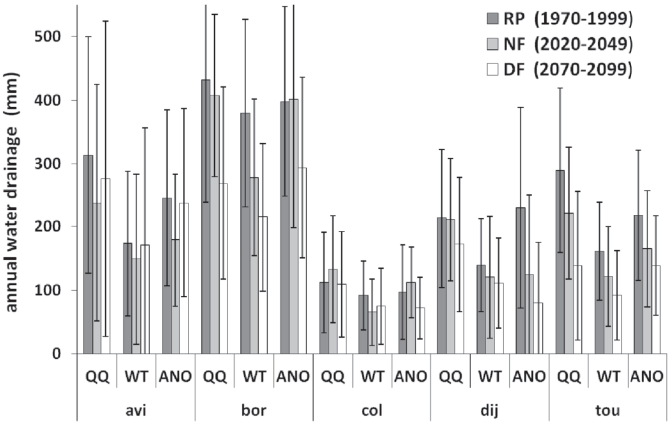

Figure 4 - Predicted changes in mean annual water drainage at 5 wine-growing locations in France; means over 30-year periods ± standard deviations; Merlot variety; A1B (~RCP6) climate scenario; QQ, WT and ANO downscaling methods; rain fed vines; 73 mm soil water holding capacity; 0.9 plants/m² density.

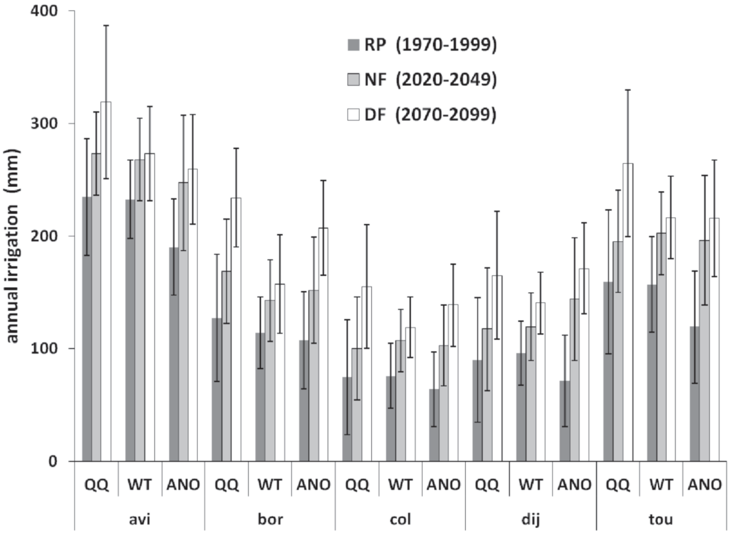

Figure 5 - Total annual quantity of irrigation water (mm) needed and sufficient to maintain ET/ETM (daily actual/maximum evapotranspiration) ratio above 0.3 at 5 wine-growing locations in France; means over 30-year periods ± standard deviations; Merlot variety; A1B (~RCP6) climate scenario; QQ, WT and ANO downscaling methods; 73 mm soil water holding capacity; 0.9 plants/m² density.

response to reduced water availability. It may also be safely assumed that, in the future, vines are likely to experience more water stress after harvest, a period of increased length and otherwise more favorable to plant activity than in the past, due to temperature and CO_2 trends.

Among other factors (results not shown), soil water holding capacity had a dominant effect on TR/TRx but resulted in a similar displacement of the TR/TRx values, with no significant change in the relative evolutions. Planting density had relatively smaller effects and did not significantly change the relative evolutions either. On average, vine variety also had quite minor effects on the TR/TRx evolution, the delay in the flowering-veraison and veraison-maturity developmental stages being insufficient to significantly modify the water status which results from long-term cumulative water fluxes. The variety effect was also smaller when the soil water holding capacity was larger and acted as a buffer.

4. Water transfer to depth

The intermittent filling of the soil volume by water leads to water being transferred downward. Therefore, drainage is a noteworthy component of the water balance and also represents the input of water for water tables at a larger scale. This aquifer recharge and its future trends were dynamically evaluated by the model as a cumulative annual flux over the agricultural year, i.e., from 1 October to 30 September.

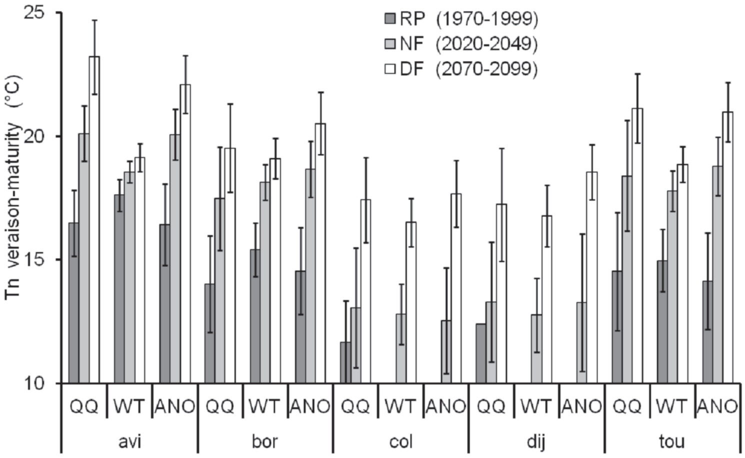

Figure 6 - Predicted changes in average minimum temperature (Tn) over the veraison-maturity period (30-year means ± standard deviations) as a function of the downscaling method (QQ, WT and ANO) at 5 wine-growing locations in France; A1B (~RCP6) climate scenario; Merlot variety. [RP Tn is missing in Colmar and Dijon because the vines did not reach maturity consistently].

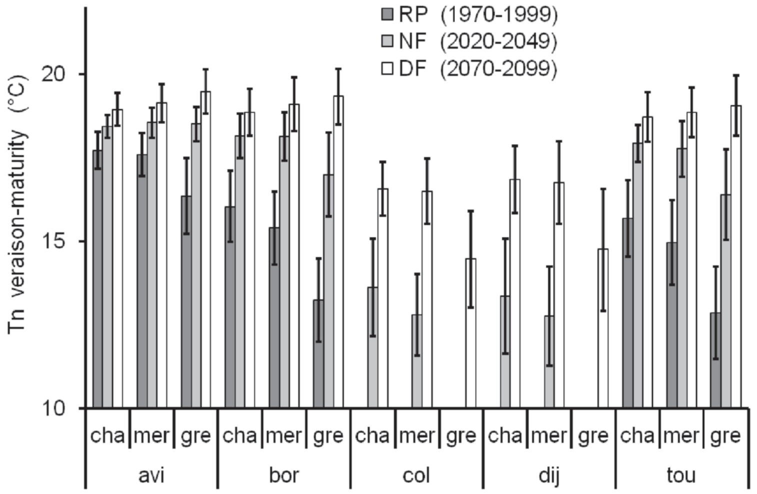

Figure 7 - Predicted changes in average minimum temperature (Tn) over the veraison-maturity period (30-year means ± standard deviations) as a function of vine variety (Chardonnay, Merlot and Grenache) at 5 wine-growing locations in France; A1B (~RCP6) climate scenario; WT downscaling method. [RP and NF Tn are missing in Colmar and Dijon because the vines do not reach maturity consistently].

The results showed that climate change will reduce the return of water to the deep groundwater in almost all locations (Figure 4). However, in Avignon and Colmar, where a decrease in TR/TRx during the veraison-maturity period was noticed (Figure 3) and where P-ET0 was already negative in the recent past, soil water balance did not exhibit a reduction in drainage (Figure 4). In Colmar, this could be explained by the already low level of drainage, whereas in Avignon, it could be explained by the high intensity of autumn rains, a specific feature of the Mediterranean climate.

The predicted overall decrease in drainage might be one of the major components of vineyard response to climate change. This observation is consistent with the rather economical use of water by usual vineyard systems: the intervening open soil surface's drying limits water losses to the atmosphere, and probably even more so in the future with less frequent rainfall. Therefore, large quantities of water are transferred to depth, particularly in rainy climates like Bordeaux (Fig. 4). It is therefore not surprising that the first impact of decreasing water availability would be a reduction in surplus drainage fluxes. This was confirmed by a clear relationship between annual water drainage and annual P-ET0 (results not shown).

However, the soil water holding capacity had a dominant effect on drainage and its likely evolution: a larger reserve enables water to be stored, which will be later evaporated or transpired into the atmosphere, thus reducing drainage values as well as forecasted changes. Therefore, a more intense impact of climate change on drainage is likely in shallow or dryer soils. These forecasted trends were mostly similar with different downscaling methods (Figure 4). Nearly identical results were obtained with the 3 vine varieties investigated and plant density also had a minor influence on this variable.

5. Theoretical irrigation requirements

The potential change in irrigation water requirements was simulated by the model, based on a theoretical water-saving system (buried drip irrigation, daily ET/ETM maintained at 0.3 or more). Unsurprisingly, all simulations consistently showed that climate change will increase irrigation requirements, even in a wetter oceanic climate like that of Bordeaux (Figure 5). However, the absolute increase was 100 mm at most and the relative increase was limited, compared to the initial recent past values, in dryer climate like that of Avignon and Toulouse. These results are consistent with the little predicted evolution of vine water status until maturation, taking into account that part of these irrigation requirements apply to the post-harvest period, when more vine water stress is likely to occur than in the past.

Calculated irrigation requirements and evolutions were higher with smaller soil water holding capacity and higher plant density (as is the case in Figure 5) and again, these quantities could be linked to the annual P-ET0.

Therefore, French viticulture sites are generally not expected to suffer much more from water stress than in the past, at least up until maturity, but the decline in water status could become truly detrimental in more southern sites, especially with a reduced soil water holding capacity, as illustrated by Avignon and Toulouse (Figure 3). Therefore, limited quantities of irrigation water could easily maintain the vine water status, provided that water remains available at a larger scale. An alternate way to maintain vine water status would be to manipulate the planting density. Both adaptation strategies would involve additional economical costs. Moreover, the decline in water tables reloading, from vineyards as well as from other crops, points to a risk for sustainable long-term water use.

6 . Heat stress and quality

Like any other summer crop, grapevine is usually harvested after the annual maximum temperature. The shift in the phenological calendar (Figure 2) will set the maturation period earlier in summer, hence in generally hotter and dryer conditions (Schultz, 2000; Jones *et al.*, 2005; Schultz and Stoll, 2010). For the maturation period, this trend thus exacerbates the effect of atmospheric warming, and the actual temperatures experienced by the plants and the grapes should increase well above the average atmospheric warming. Moreover, studies have shown the relevance of the average minimum temperature during the pre-harvest period for grape quality assessment, particularly for phenolic secondary compounds and aromas (Tonietto and Carbonneau, 2004). The "night coolness index" was here adapted merely by calculating the average minimum temperature (Tn) during the predicted veraison-maturity period. The forecasted evolutions of this indicator showed a clear change in maturation conditions towards much higher temperatures (Figure 6) and therefore towards a risk of sharp grape quality decline (Tonietto and Carbonneau, 2004; Downey *et al.*, 2006; Dai *et al.*, 2011). Nearly the same predicted evolutions were observed in all the sites, with still some north-south climate differences, but here the downscaling method seemed to have some influence on the results since the WT downscaling method consistently predicted more moderate changes (Figure 6). Obviously, all soil- and canopy-related parameters had no influence on these results. However, different vine varieties led to different predicted evolutions (Figure 7): as expected, the later variety tested, Grenache, exhibited a lower veraison-maturity Tn in the recent past but a stronger predicted increase in the future compared with the relatively early variety Chardonnay. At a given site, this differential evolution led to nearly homogenous distant future Tn values and even to a slightly reversed ranking (Avignon, Bordeaux, Toulouse) (Figure 7). This compensating effect was simply due to the combination of earlier phenology and annual temperature evolution pattern: among the limited set of vine varieties that were tested, all the distant future maturation periods are likely to take place close to the annual maximum of temperature. Nevertheless, in the near future, the Tn-wise ranking of varieties will remain unchanged, even if the differences between them are greatly reduced.

The French viticulture sites, and particularly the southern sites, are therefore likely to face a major challenge since the expected magnitude of climate change is such that all simulations supported potentially harmful effects on grape quality. The adaptation of the vineyard systems to these changing conditions might involve soil and canopy management techniques (for instance giving up leaf removal around grapes, plantations on north-exposed slopes, and cooling techniques), but with rather limited efficiency and/or obvious technical or economical limitations. Even using later varieties could be only of short-term value, as already suggested in a more specific context (Duchêne *et al.*, 2010).

CONCLUSION

As indicated by the simulation results in several viticulture sites in France, climate change is likely to influence primarily grapevine phenology and hence the spatial distribution of climatic suitability for grape growing. Between the recent past and the end of the 21st century, the entire growing cycle will be brought forward by 20-40 days.

As one of the consequences of phenological earliness, large and harmful impacts are predictable on the maturation thermal conditions and thus on grape quality, especially in terms of polyphenols and aromas. Increases in temperature during the maturation period could reach at least 5°C by the end of the century in the traditional wine-growing sites. However, few crop system parameters are able to mitigate the predictable phenology evolution and its consequences on maturation conditions. Even changes in vine variety are unlikely to provide a long lasting solution to the intense warming during the maturation period, unless varieties later than Grenache are to be considered. On the other hand, the water status of grapevine should experience a moderate decline up until maturation, although it could become crucial for some southern vineyards. However, post-harvest vine water stress could become a true issue. Moreover, vineyards should transfer much less water to depth, thus reducing aquifer reloading.

Locations and climate series where more intense changes in P-ET0 are expected should face the strongest impacts on vine water status and water drainage. The results of these simulations are also sensitive to the soil water holding capacity and, to a lesser extent, to the vine variety and the planting density. Schematically, climate change impacts on vineyard water budget components should be more intense with shallow or dryer soils and higher planting density.

Most simulation results were little influenced by the downscaling method used to produce the input climate series. Therefore, reduced uncertainties are associated with the main trends displayed and the order of magnitude of the effects of climate change on vineyards. However, the WT downscaling method led to a more moderate predicted evolution of thermal conditions during the maturation period. More uncertainty is therefore linked to this point.

Potential means for the relatively easy systemic adaptation of the vineyards with respect to vine water status could be irrigation, if water remains available at a low cost, or reduced planting density, also with economical consequences that are difficult to predict. On the other hand, with respect to maturation conditions, it should be very difficult to escape the harmful effects of climate change. To some extent, however, an adaptation of the vineyard systems and techniques could be considered for the short term, for instance discarding leaf removal, cooling by irrigation, using north-facing slopes, etc. Changes in vine variety could prove ineffective in the long run, unless very late varieties become acceptable or other ways to adapt the genetic material to warmer conditions are to be found.

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A NEW INTEGRATED APPROACH TO ASSESS THE IMPACTS OF CLIMATE CHANGE ON GRAPEVINE FUNGAL DISEASES: THE COUPLED MILA-STICS MODEL

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Abstract

Climate change is expected to influence the development and occurrence of fungal crop diseases. We therefore need to understand and predict the impacts of climate change on crop biotic stresses. A clearer understanding of these impacts requires consideration of how plants respond to climate change, as host plants provide a microclimate and physical and trophic support for disease development. Models have been developed to predict disease pressure on grapevine, but climate change is expected to generate complex responses that require a more integrated view of plant-pathogen interactions. We present here a new, integrated approach using the process-based MILA model coupled with the STICS crop model in order to understand and predict the potential impacts of climate change on downy mildew epidemics affecting grapevine (*Plasmopara viticola*). We first describe MILA and its calibration to downy mildew. The MILA-STICS combination has then been applied to future climatic data. Analysis of the general trend for future disease pressure, on the one hand, and the effects of the host plant on the course of certain processes, on the other hand, have demonstrated the value of applying MILA to the context of climate change. As a model that attempts to integrate the different mechanisms thatwhich explain involved in disease development, MILA is an appropriate tool to understand and assess the contribution of different effects on disease pressure. Finally, we describe some of the limitations of applying process-based models to the context of climate change. It is necessary to overcome these obstacles to ensure their effective use.

Key words: climate change, integrative integrated approach, plant-pathogen interactions, process-based model, fungal crop diseases

Résumé

Le changement climatique devrait influencer le développement et l'apparition de maladies fongiques des cultures. Nous avons donc besoin de comprendre et de prédire les impacts du changement climatique sur les stress biotiques des cultures. Une meilleure compréhension de ces impacts nécessite de considérer les effets du changement climatique sur les cultures, la plante hôte fournissant un microclimat ainsi qu'un soutien physique et trophique pour le développement de la maladie. Des modèles ont été développés pour prédire les pressions de maladies fongiques de la vigne, mais le changement climatique devrait générer des réponses complexes qui exigent une prise en compte plus intégrative des interactions plante-pathogène. Nous présentons ici une nouvelle approche intégrée en utilisant le modèle MILA couplé avec le modèle STICS afin de comprendre et de prédire les impacts potentiels du changement climatique sur les épidémies du mildiou de la vigne (*Plasmopara viticola*). Nous décrivons d'abord MILA et sa calibration à des données observées de sévérités de mildiou. Les modèles couplés MILA-STICS ont ensuite été appliqués dans le contexte du changement climatique. L'analyse de la tendance générale de la pression de maladie, d'une part, et les effets de la plante hôte sur la réalisation de certains processus, d'autre part, ont démontré l'intérêt d'appliquer MILA au contexte du changement climatique. En tant que modèle visant à intégrer les différents mécanismes qui expliquent le développement des maladies, MILA est un outil approprié pour comprendre et évaluer la contribution de différents effets sur la pression de la maladie. Enfin, nous décrivons certaines des limites de l'application de modèles basés sur les processus dans le contexte du changement climatique. Il est nécessaire de surmonter ces obstacles afin d'assurer une plus grande efficacité de leur utilisation.

Mots clés : changement climatique, approche intégrativeintégrée, interactions plante-pathogène, modèle basé sur les processus, maladies fongiques des cultures

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INTRODUCTION

Major shifts in temperature and changes to the seasonal patterns of rainfall distribution are currently affecting most of the world. Climatic projections suggest that these trends will continue in the decades to come, affecting both mean and extreme values of these variables (Easterling, 2007). In the latest report from the Intergovernmental Panel on Climate Change (IPCC), mean global temperature is estimated to increase by between 1.8°C and 4.0°C (with a likely range of 1.1–6.4°C) by the end of the present century, depending on the greenhouse gas emission scenario (Easterling, 2007).

As the onset and course of fungal crop diseases are both strongly dependent on weather conditions, climate change is expected to influence the occurrence and development of these diseases and may alter the geographical distribution of pathogenic species (Chakraborty and Newton, 2011). Changes to temperature and rainfall patterns could directly affect the survival, development and reproduction of pathogens. For instance, dryer summer conditions may reduce the incidence of pathogens that require free water or saturated soil for infection to occur (Coakley *et al.*, 1999). Changes to disease occurrence and development may also be affected by the host plant's response to climate change. For example, many pathogens only affect their host plant during specific vulnerable periods of the plant life cycle. An advance or delay in the host's development caused by climate change could modify the timing between its vulnerable stage and the pathogen's period of development (Coakley, 1988). Another example is the potential increase in plant biomass production promoted by a rise in temperature and in the CO_2 content of the atmosphere. This biomass could then constitute a larger trophic reservoir for pathogens to colonize and multiply in. This reservoir would be available earlier, allowing epidemics to start when seedlings are potentially more vulnerable and leading to longer periods of potential biotic pressure on crops (Luck *et al.*, 2011). However, it can be expected that pathogen populations will adapt to climate change. Studies have already demonstrated the genetic adaptation of pathogen populations to elevated CO_2 concentrations (Chakraborty and Datta, 2003), higher temperatures (Gijzen *et al.*, 1996) and changes to rainfall (Travers *et al.*, 2007).

Several recent studies have described new or emerging diseases (Rosenzweig *et al.*, 2001), such as soybean sudden death syndrome (*Fusarium solari* solani f.sp. *glycines*) in North America (Scherm and Yang, 1999) or grey leaf blight of corn (*Cercospora zeae-maydis*) in the USA (Anderson *et al.*, 2004).

We therefore need to understand and predict the impacts of climate change on crop biotic stresses, especially in light of the trend towards reduced use of pesticides because of their proven impacts on the environment and human health. To better understand these impacts, it is necessary to consider the response of plants to climate change, as a host plant may provide a microclimate and physical and trophic support for disease development.

Grapevine is affected by several types of pest and diseases, including mites (e.g. *Eotetranychus carpini*), insects (e.g. the European grapevine moth *Eupoecilia ambiguella*), phytoplasmas (e.g. Flavescence dorée transmitted by the leafhopper vector *Scaphoideus titanus*) and fungal diseases. Among the latter, powdery mildew (*Erysiphe necator*), downy mildew (*Plasmopara viticola*) and grey mould (*Botrytis cinerea*) are known to have serious effects on both yield and quality. The pressure of these diseases could be modified under a changing climate, and in differing ways according to the pathogens concerned. Pathogens display different responses to climate (e.g. powdery mildew can reproduce under conditions of low relative humidity and without a need for water, whereas downy mildew is strongly moisture-dependent) and interact differently with the host plant. Some effects of climate change have already been seen with respect to grape fungal diseases. Some recent observations have demonstrated an increased frequency of downy mildew and powdery mildew attacks since 2004 in the Champagne vineyards (France), the fungi notably enjoying the warmer temperatures experienced in this region ("Comité Interprofessionnel des Vins de Champagne", pers. com.). However, it was also shown that powdery mildew had less impact in terms of disease severity in a particularly warm year (2003) when compared to an average year (1998) (Calonnec *et al.*, 2008).

Two main ways are currently used to understand and quantify crop disease dynamics and impacts: experimentation and modelling.

Experimentation can be used to identify influential factors and the host-pathogen interactions involved and to provide pathogen response functions for various variables. Many studies on host-pathogen interactions have revealed ontogenic resistance against grape pathogens (Lee *et al.*, 2012; Steimetz *et al.*, 2012; Kennelly *et al.*, 2005; Reuveni, 1998; Gadoury *et al.*, 2003). As for the effect of climatic variables, for example, Lalancette *et al.* (1988a) determined the infection efficiency of *Plasmopara viticola* on grapevine under a range of wetness durations (1–15 hours) at six fixed temperature levels (5°C–30°C) in a growth chamber. Under a changing climate, experimentation could also enable the exploration of yet unknown mechanisms that are likely to evolve. One striking example concerns the potential effects of a higher carbon dioxide levels on disease development, which are now being studied for some pathogens (Pugliese *et al.*, 2011; Titone *et al.*, 2009; Lake and Wade, 2009). Such experimental findings are essential to building and improving epidemiological models that are particularly relevant to impact studies on climate change.

Modelling approaches can provide information on crop disease dynamics in a future climate, under many different conditions and taking account of the complexity of climate-pathogen or climate-host-pathogen interactions. Many epidemiological models, both empirical and mechanistic, have been developed to simulate the development of grapevine diseases (Orlandini *et al.*, 2008; Salinari *et al.*, 2006; Calonnec *et al.*, 2008; Calonnec *et al.*, 2011; Caffarra *et al.*, 2012; Park *et al.*, 1997; Tran Manh Sung *et al.*, 1990; Rossi *et al.*, 2008; Stryzik, 1983). Some of these models have tried to integrate host-pathogen interactions by simulating the spatiotemporal spread of the disease in relation to plant architecture (Calonnec *et al.*, 2011; Calonnec *et al.*, 2008), or to integrate interactions at a tri-trophic level (Caffarra *et al.*, 2012). Some of these models have been applied in climate change impact studies. For example, Salinari *et al.* (2006) used an empirical statistical model to study downy mildew outbreaks on grapevine under climate change. They predicted that initial disease outbreaks at several sites throughout the world might occur earlier in the 2030s, 2050s and 2080s under the highest temperature increase scenario of climate change. Caffarra *et al.* (2012) combined a phenological model of grapevine with a model for powdery mildew epidemics (based simply on the length of latency periods) in order to consider modifications to the window of susceptibility to powdery mildew under climate change. They found a reduction in the susceptibility window and a decrease in disease severity in the eastern Italian Alps.

Nevertheless, it is anticipated that climate change will generate complex responses that require a more integrated approach to host plant-pathogen interactions. It is therefore necessary to develop tools that integrate the different mechanisms which explain disease development and could be relevant to understanding future trends. In most cases, the various indirect effects of climate change via the host plant are not taken into account.

This paper presents a new, integrated approach using the MILA model (Caubel *et al.*, 2012) in order to understand and predict the potential impacts of climate change on downy mildew epidemics affecting grapevine. This process-based model integrates the effects of various factors on disease development. Its

Table 1. The different MILA simulation options and those selected in the case of downy mildew of grapevine (in bold type).

Processes simulated by MILA	Option of simulation 1	Option of simulation 2	Option of simulation 3
Provision of primary inoculum	Primary inoculum directly infectious	**Not directly infectious (depending on rain and air temperature)**	▨
Dispersal	Always possible	**By rain**	▨
Deposit	**On leaves**	On fruits	On flowers
	No effect of leaf age on the surface of deposit	**Effect of leaf age on the surface of deposit: young leaves susceptible**	Effect of leaf age on the surface of deposit: old leaves susceptible
Infection	Function of crop temperature	**Function of crop temperature and surface wetness duration**	▨
Latency	Function of crop temperature	Function of crop temperature and crop relative humidity	▨
2nd inoculum production	Function of crop temperature	Function of crop temperature and crop relative humidity	**Function of crop temperature and nocturnal crop relative humidity**
	No effect of lesion age	Effect of lesion age	▨
	No effect of leaf nitrogen content	Effect of leaf nitrogen content	▨
Lesion lifespan	**Constant**	Function of crop temperature	Function of crop temperature and crop relative humidity
Spore lifespan	Constant	Function of crop (or air) temperature	**Function of crop temperature and crop relative humidity**

coupling with a crop model enables a dynamic consideration of the effects of different plant factors during the crop cycle.

A NEW APPROACH TO STUDYING THE IMPACT OF CLIMATE CHANGE ON GRAPEVINE FUNGAL DISEASES: THE MILA MODEL

1. Description and adaptation of MILA to downy mildew

MILA (Figure 1) simulates successive epidemiological cycles at the crop level and at a daily time step. Its conceptual design was described in Caubel *et al.* (2012): for each module, corresponding to the simulated epidemiological processes, several response functions are proposed that correspond to different responses by the pathogen to climate, the microclimate within the crop canopy, plant growth and development, and trophic status variables (Table 1).

This generic framework enables the simulation of disease dynamics in different plants. Plant variables are provided at a daily time step using a process-based crop model that is dynamically coupled with MILA (Figure 1). MILA then calculates disease severity at the daily time step, and feedback to the crop model consists in the daily reduction of the photosynthetic surface as a function of the increase in the diseased surface area (Figure 1).

During this study, we coupled MILA with the STICS crop model (Brisson *et al.*, 2008). In order to adapt MILA-STICS to the specific case of downy mildew epidemics on grapevine, we selected, for each MILA module, the simulation option (Caubel, 2012) best suited to grapevine downy mildew (Table 1). The primary inoculum is not directly infectious and its provision is simulated according to a maturation and germination process (Park *et al.*, 1997; Tran Manh Sung *et al.*, 1990). Dispersion is mainly assured by rain splash (Emmett *et al.*, 1992) and the surface of the deposit depends on leaf age, with young leaves being more susceptible than old ones (Reuveni, 1998). Some conditions of temperature and leaf wetness duration enable the infection process (Lalancette *et al.*, 1988a), and the length of the latency period depends on temperature and humidity conditions (Goidanich, 1958). As for the production of secondary inoculum by lesions, downy mildew is mainly dependent on the temperature and moisture conditions at night (Lalancette *et al.*, 1988b). Finally, we assumed that the lifespan of lesions is constant and that of spores varies according to temperature and moisture conditions (Blaeser and Weltzien, 1978).

MILA was calibrated (Caubel, 2012) using the disease severities observed several times during the crop cycle on eleven plots at various sites in France and in different years (Figure 2). The initial MILA values were set in line with experimental measurements from the literature, and the input variables (climate, soil, variety, technical practices) of the grapevine version of STICS were informed according to plot conditions. A sensitive analysis then enabled identification of the parameters exerting a strong influence on MILA: these parameters were optimized by minimizing the root mean square error (RMSE) between simulated and observed disease severities. The error of prediction for

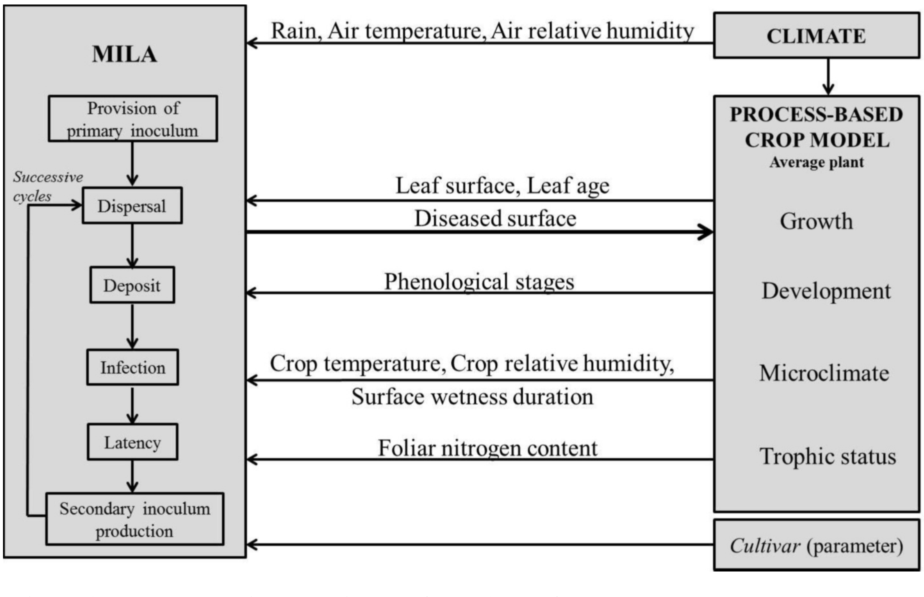

Figure 1. Modules and input variables of MILA and feedback to the coupled crop model.

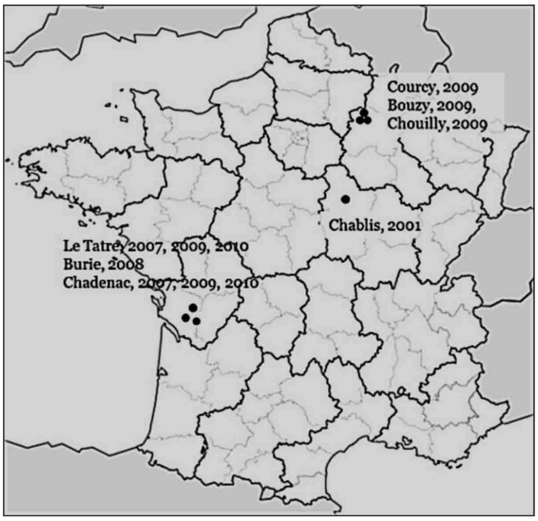

Figure 2. Database used to calibrate and evaluate MILA-STICS in the case of downy mildew of grapevine.

MILA-downy mildew was calculated by cross validation (Wallach, 2006): its value of 10.66% was satisfactory (Figure 3).

2. Use of MILA to study the impacts of climate change on downy mildew of grapevine

In order to illustrate the type of questions that can be addressed with MILA-STICS, we chose to focus on analyzing a limited number of output variables. We looked at the general trend for future disease pressure and then focused on certain processes (the infection process and the provision of primary inoculum) and how the host plant affected their achievement. We first looked at the evolution of the area under the disease progress curve (AUDPC) in order to characterize the evolution of disease development. The AUDPC was calculated as the sum of the daily disease severity (as a percentage of total leaf surface area) between flowering and physiological maturity in order to consider the majority of disease development. We then focused on the infection process and the provision of primary inoculum in order to illustrate how intermediate MILA variables and the coupling of MILA and STICS could help us to explain the evolution of disease development. Concerning the infection process, we studied the evolution of the frequency of days favourable to infection during the crop cycle as a function of microclimatic conditions within the crop (crop temperature and leaf wetness duration). Lastly, concerning the provision of primary inoculum, we focused on the evolution of the timing between grapevine bud break and the arrival of the first infectious spores from the primary inoculum. Indeed, after a period of survival, the primary inoculum is able to attack grapevine leaves after a process of maturation and germination according to a Gaussian curve over time (provision of primary inoculum).

A theoretical framework of numerical experimentations limited in terms of their representativeness of different sites, soils, varieties and cultural practices was used to illustrate these results. The study was performed for three representative locations in France (Bordeaux, Avignon and Dijon). The present and future climates were simulated using the global climate model ARPEGE (Gibelin and Deque, 2003), with a grid of approximately 50 square km side-on over France. The model was forced by applying an effective greenhouse effect corresponding to the SRES A1B scenario,

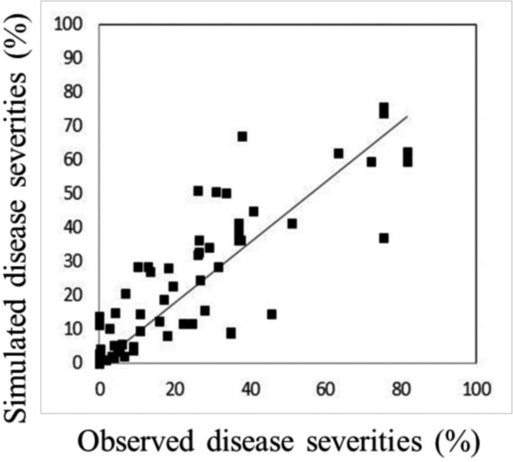

Figure 3. Disease severities (%) simulated by MILA (cross validation) according to observed disease severities (%).

representing a balanced scenario that corresponded to atmospheric concentrations of 541 ppm by 2046-2065 and 674 ppm by 2081-2100. The Quantile-Quantile downscaling method (Deque, 2007) was therefore applied to obtain data for the three locations. Under these assumptions, an average warming of about 2.5°C–3°C was predicted for the three production sites by the end of the present century, and a more marked rise in summer temperatures was expected. Less rainfall was predicted, particularly in summer and in the south-west of France (Bordeaux). Simulations were performed for the Chardonnay variety using one type of soil: a leached brown soil, 120 cm deep, with a useful water reserve of about 150 mm and an organic matter content on the surface horizon of 1.5%.

The temporal evolutions of the selected variables were analyzed and compared statistically (Tukey's Honestly Significant Difference tests) between three climatic periods: recent past (RP, 1970-2000), recent future (RF, 2020-2050) and far future (FF, 2070-2100).

The results of our study showed that the global evolution of disease development would decline in the distant future at Bordeaux and Dijon, whereas it would remain unchanged at Avignon (Figure 4). It is interesting to note that the length of the period separating flowering from physiological maturity, as simulated by STICS, would decrease in the future at all three sites: consequently, the AUDPC was integrated for a shorter period. However, an analysis of the normalized AUDPC, enabling a comparison of the direct effects of future climate conditions independently of their effect on host phenology, showed that they would decrease anyway (results not shown).

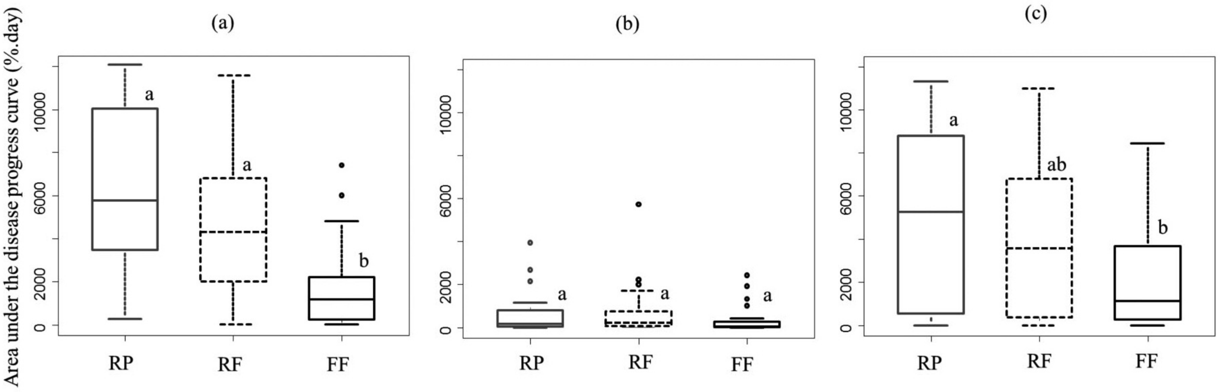

Figure 4. Evolution of the area under the disease progress curve (%.day) between flowering and physiological maturity at (a) Bordeaux, (b) Avignon and (c) Dijon for the three climatic periods (RP, recent past, 1970-2000; RF, recent future, 2020-2050; and FF, far future, 2070-2100); different letters indicate significant differences between climatic periods.

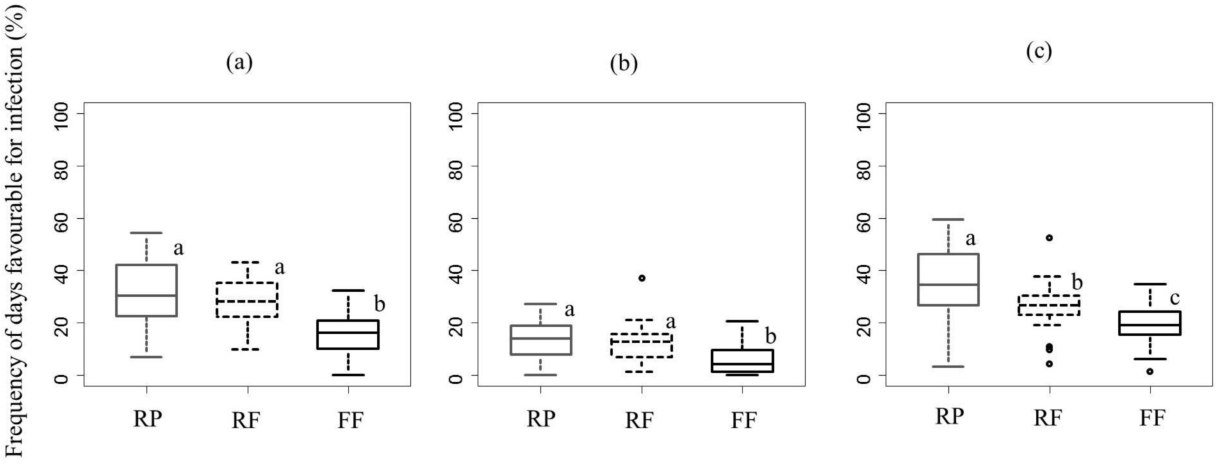

Figure 5. Evolution of the frequency of days favourable to downy mildew infection during the crop cycle (%) at (a) Bordeaux, (b) Avignon and (c) Dijon for the three climatic periods (RP, recent past, 1970-2000; RF, recent future, 2020-2050; and FF, far future, 2070-2100); different letters indicate significant differences between climatic periods.

Concerning the achievement of the infection process, the evolution of the frequency of days favourable to infection during the crop cycle according to crop temperature and leaf wetness duration would decrease in the recent future at Dijon and in the far future at Bordeaux and Avignon (Figure 5). This trend could mainly be attributed to a reduction in leaf wetness duration in the future at the three sites, but also to the unfavourable effect of the rise in crop temperature beyond optimum values at Avignon and Bordeaux (southern sites) during the summer.

As for the provision of primary inoculum, the time elapsing between grapevine bud break and the arrival of the first infectious spores from the primary inoculum would probably be modified. MILA did not predict any change in the date of arrival of the first infectious spores from the primary inoculum under a changing climate. By contrast, STICS simulated an average advance of bud break of 10 days at Avignon, 5 days at Dijon and 20 days at Bordeaux in the far future. So, whereas the first infectious spores were potentially in contact with a physical support in only 65% of cases in the recent past, they would be able to infect grapevine systematically in the far future, as bud break will have occurred before their arrival.

This theoretical analysis using limited numerical experimentations enabled an assessment of the type of information made available using this type of integrated approach. Among the effects simulated, that of the microclimate within the crop on the infection process and that of the plant as a physical support (present or not at a given moment) on disease initiation, which were not observed in other studies in other studies, appeared to be very important to our understanding of the evolution of disease pressure.

During this study, we showed that MILA, as a process-based model trying to integrate the different mechanisms that explaininvolved in disease development, was an appropriate tool to understand and assess the contribution of different effects on disease pressure. It enabled the identification of these processes and the factors that could explain a general trend for the evolution of a given disease pressure (disease severity, AUDPC) by analyzing the intermediate variables that characterized completion of a stage in the epidemic cycle (infection rate, latency period, etc).

However, its use could be improved. For example, its coupling with a plant architectural model rather than a 2D crop model would allow key mechanisms involved in the dynamics of certain pathosystems to be taken into account. Indeed, plant architecture, which is modified throughout the crop cycle as a function of plant development and technical management, could be a determining factor in pathogen dispersion by affecting the distance between organs or by modifying the number of organs (Calonnec *et al.*, 2008). It can also modify the microclimate within the crop and hence influence infection and inoculum production (Pasco *et al.*, 2012; Leca *et al.*, 2012).

Moreover, the calibration and evaluation of MILA requires measurements of disease severity at different contrasting sites that are not always available. For this reason, MILA has not yet been validated for several French vineyards. One crucial challenge will therefore be to provide support for projects that aim to acquire observational data on disease pressure in the field or on pathogen responses to various factors under controlled conditions.

To conclude, the principal advantages of MILA derive from its generic framework, which means it can be adapted to different plant diseases, and from its ability to be coupled with a crop model so as to take account of the indirect effects of climate via the host plant. The use of pesticides tends to decline, and food security at a global scale needs to be assured. The diagnostic information generated by MILA could therefore be used to assist in the definition of new cropping systems.

DISCUSSION AND CONCLUSION

Process-based crop models are appropriate tools to predict and understand the impacts of climate change on plant-disease systems, but their use in this context is affected by certain limitations. If they are to be used more efficiently, then these obstacles can be overcome.

These limitations include the identification establishment of parameter values to characterize the response thresholds and response functions relative to certain factors and according to experimental data obtained within limited ranges. However, these ranges could be potentially modified in the context of climate change. This problem is largely shared by the modelling community with respect to the validity of temperature response functions under hotter temperatures (Kim *et al.*, 2007; Grant *et al.*, 2011).

In addition, it is important to consider and study potential evolutions of host plant resistance and host-plant interactions (Dyck and Johnson, 1983; Kolmer, 1996) and the genetic evolution of fungal species (Pangga *et al.*, 2011) in response to environmental changes (Chakraborty and Newton, 2011). Their integration would improve the predictive capacity of current process-based models used in the context of climate change.

Moreover, several environmental factors are usually not included in the models used at present, even though they are likely to evolve in the context of climate change and might influence disease development and plant-disease interactions. These include the potential effects of changes to atmospheric concentrations of ozone and carbon dioxide on disease development and plant-disease interactions (Tiedemann and Firsching, 2000; Chakraborty and Newton, 2011).

It is therefore necessary to pursue the acquisition of experimental data in order to improve the use of models in the context of climate change. These data could enable the addition of mechanisms not taken into account as yet, or the modification of response functions and parameters already included in the models.

The use of process-based models in the context of climate change raises the question of relevant variables that might be includedthe variables that might be relevant to include, and also the question of the timescale for the mechanisms thus simulated. Indeed, it is better to simulate some mechanisms at an hourly time step. For example, the use of hourly rain inputs to simulate the infection process is relevant in order to take account of the effect of interruptions in wetness periods on the infection. Unfortunately, the hourly time step is not adapted to studies in the context of climate change because the disaggregation of future daily precipitations into hourly sections is still unreliable.

Finally, it is important to recall that any climate change impact study requires the use of different climate change scenarios and downscaling methods so that account can be taken of the uncertainties attached to future climatic predictions.

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VITICULTURE AND ADAPTATION TO CLIMATE CHANGE

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The aim of this article is to lay out a series of issues of current concern to researchers in the social sciences, regarding the impact of climate change on the vine and wine sector. The challenge lies in evaluating the cost of transition from one system to another through an integration of the direct and indirect effects of climate change. This adaptation, whether reactive or anticipatory, combines technical and organisational innovations with localisation strategies and institutional changes. Such actions could either try to maintain the existing situation as much as possible or could try to bifurcate towards deep changes, entailing very different costs. Given the multitude of uncertainties at play, not to mention the necessity for continuous adaptation to an ever-changing climate, these costs are hard to quantify. This article will illustrate two sets of measures for wine cultivation adaptation: 'no regrets' measures, which offer immediate benefits, and 'reversible and flexible' measures, which limit the inertia of wine-cultivating systems. In spite of the challenges, what stands out is the evident re-enforcement resulting from the collaboration between researchers and political and economic actors. In the field of wine cultivation, these collaborations can follow two paths: the study of the diversity of existing wine-growing systems and genetic resources or the possibility of more radical technological and social experimentation.

INTRODUCTION

Wine cultivation depends heavily on climate, which influences both the development of the vine and the quality of the wine that is produced from its grapes, and for this reason, it has become a point of reference for the study of the effects of climate change (Jones and Webb, 2010; Seguin, 2010). On top of this, it can also act as a laboratory of sorts for the analysis of climate change adaptation strategies. The many levers that have helped grape and wine production to evolve have indeed combined with technical innovations, localisation strategies and institutional changes (Holland and Smit, 2010; Ollat and Touzard, 2011). To pursue these issues further, we will consider here a series of questions raised by the social sciences concerning adaptation to climate change and apply them to climate change and the vine. After a brief summary of the characteristics of climate change and its impact on human activities, we will present the lessons learned from research into this adaptation and the questions it raises for wine cultivation. We will then outline how different types of robust measures could be appropriately applied to wine cultivation.

A MAJOR CHANGE

Climate change will result in a rapid evolution of the climate, an evolution that can be evaluated with the aid of national and international climactic projections (see for instance Jouzel *et al.*, 2012 for climate evolution in France). As it is not possible to predict future greenhouse gas (GHG) emissions, projections are based on scenarios, that is to say, possible changes in global emissions up to the year 2100. Following this method the IPCC (Intergovernmental Panel on Climate Change) constructed a collection of contrasting scenarios for GHG emissions to serve as a basis for international exercises in climate simulation. A first set was constructed in 1990 (Nakicenovic *et al.*, 2000), and it was recently enriched by a new collection of scenarios which is used for climate projections of the latest IPCC report (Moss *et al.*, 2008; Moss *et al.*, 2010). An example of such a scenario is the SRES A2 scenario, which is frequently used as a reference; it presumes a rapid increase in global population and economy, an absence of climate policies, and a considerable increase in GHG emissions, consistent with current trends. The projections based on this scenario forecast an average increase in temperature of about 3 °C by the end of the century (IPCC, 2007).

This increase in temperature may initially appear to be relatively small. It is small, indeed, when compared with daily and between-season temperature variation. We must not, however, be fooled by these figures, as the variation in climate associated with this variation in temperature leads to profound changes in precipitations and meteorological extremes that do not show up on this one indicator.

A good illustration can be found in the work of Hallegatte *et al.* (2007), who investigated the similarities between a selection of large European cities in terms of temperatures and precipitations, as projected by two climactic models of the A2 emission scenario. From the simulations presented in Figure 1 and Figure 2 (the Hadley Centre and Météo-France, respectively), it can be conjectured that in 2100, Paris will have the same climate as Cordoba (southern Spain) and Bordeaux (southwestern France) have now. The climate of

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Marseille might also approach that of Cordoba or Greece. This approach makes it easier to anticipate the adaptation France needs to make, based on this climate forecast.

CONSEQUENCES FOR HUMAN SOCIETY

Why is climate change a serious issue? In fact, putting aside certain extreme cases (e.g., desert climates), it would be hard to argue that some climates are better adapted for man than others, and it is difficult to justify the claim that future climates will be more detrimental than current climates. Taking the above example again, there is no reason to believe that the climate of Cordoba would be worse for Parisians than Paris's current climate.

On the other hand, lifestyle and infrastructure differ greatly between these two cities, as do production and agricultural techniques in surrounding areas. They are adapted to their respective local climate. The situation becomes serious when, for one reason or another, people are not well adapted to their climate. The heat wave of 2003 is a very good illustration: the high temperatures resulted in significant damage in Paris (Hémon and Jougla, 2004), whereas these corresponded to normal summer temperatures in the south of Spain, where they do not lead to such tragic consequences (Hallegatte *et al.*, 2007).

The same applies to wine cultivation. Optimal climatic conditions for fine quality wines are diverse, as can be illustrated by Moselle in Germany, Burgundy, Bordeaux or the Cotes du Rhone in France, and the Napa Valley in California. The choice of grape variety, cultivation and wine-making techniques, and the laying out and localisation of plots have allowed wine production to extend across a wide range of soil and climate conditions (Tonietto and Carbonneau, 2004) and to respond to market demands, which value differentiation between products. Climate change is already affecting most wine-growing regions, with effects

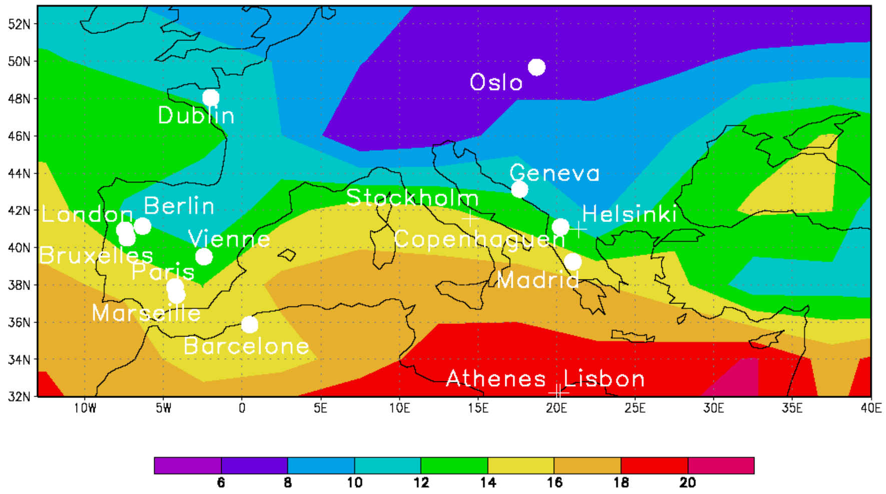

Figure 1 - Climactic analogues in 2070, Hadley Centre model, scenario SRES A2 (Source: Hallegatte *et al.*., 2007).

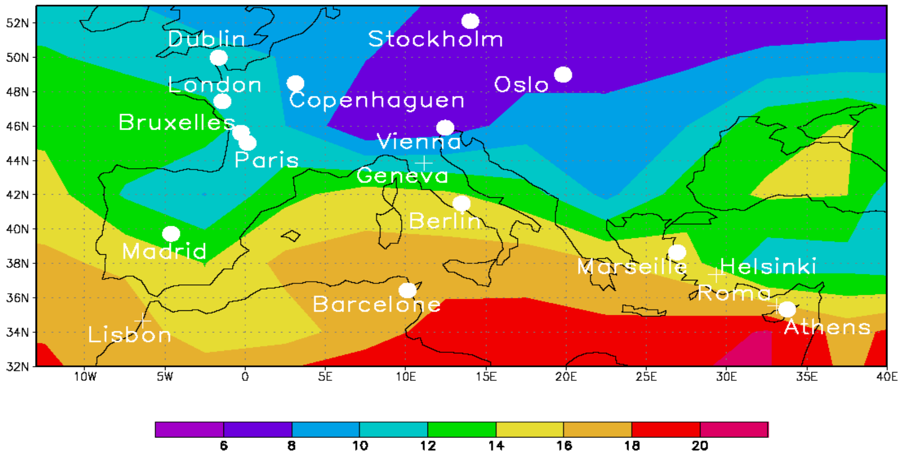

Figure 2 - Climactic analogues in 2070, Météo-France model, scenario SRES A2 (Source: Hallegatte *et al.*, 2007).

on the date of harvest (earlier), the composition of grapes and wine (higher alcohol content), and, to varying degrees, the vine's water comfort, crop development and yield. These effects do not necessarily threaten vine's viability or grape production, but they do raise questions about wine-cultivating systems and established quality. However, the transition from one production system to another in order to maintain or regain a quality/yield ratio that will be economically viable raises uncertainties and concerns over the likely cost. One of the principal challenges climate change presents is therefore to know if and how the transition can be managed, what investment it will call for, and how will regions succeed in making the transition from being adapted to current climate conditions to being adapted to projected future conditions for the next few decades.

There are some further difficulties : if it is never simple to adapt human activities, it should not be forgotten that it is not humanity alone that will have to adapt. Flora and fauna, and more generally the ecosystems that surround us, must also adjust, and it is by no means sure that they will survive unscathed, in view of the high rate of climate change when compared to geological climate change. Ecosystems operate in a very integrated manner, and the disappearance of certain species may set off a chain reaction amongst other species. These changes, which may be wide-ranging and extremely difficult to predict (IPCC, 2007), will also have an impact on human society, in addition to the direct impact of climate variation. We must therefore adapt to this double change : the change in climate and the change in the environment caused by climate change.

There are two ways of approaching adaptation to all these changes (Smit *et al.*, 2000). Adaptation can be reactive, that is to say, an ex-post response to an observed impact of climate change. It can equally be anticipative, that is to say, planned for and put in place before adverse impacts occur, with the aim of limiting the vulnerability of existing productive, social and ecological systems. From a political point of view, anticipative management is often more difficult to put in place than reactive management, but the associated gains are generally much greater (Hallegatte *et al.*, 2011 ; Hallegatte, 2010).

HOW CAN WINE CULTIVATION BE ADAPTED TO CLIMATE CHANGE ?

Approaches to climate change adaptation can broadly be defined as 'the set of actions and processes (technical change, organisational change, localisation) that societies must take to limit the negative impacts of the changes and maximize their beneficial effects' (De Perthuis, 2010 ; Hallegatte, 2010). In the case of wine cultivation, different types of adaptive actions exist, which are very different in nature and scope. They can be identified for example by reconsidering the human interventions that have shaped the current diversity of cultivated vines, sometimes in extreme conditions (e.g., in mountain and tropical areas).

First, **technical changes** are possible at different stages of the production chain : the choice of grape variety and its rootstock can improve resistance to drought, hold back the advance of the maturity date and modify the sugar content of the fruit (Duchêne *et al.*, 2010) ; new pruning methods can affect the exposure of the fruit and the micro-climate of the canopy (Jones *et al.*, 2005) ; irrigation can optimise the water balance (Carbonneau and Ojeda, 2012) ; and oenological practices can limit the 'defects' associated with climate change (e.g., reduction in alcohol content) or promote new aromatic flavours (Holland and Smit, 2010). There are potentially many variations of these technical innovations, with different costs and different levels of uncertainty regarding their effects on the wine production system and the quality of wines produced. One of the challenges is to anticipate their effects and to test them locally, which cannot be fully evaluated ex-ante.

These technical changes are generally tied to **organisational and localisation changes**, which constitute other levers of adaptation (Ollat and Touzard, 2011). Thus, the choice of vineyard management practices, the reorganisation of grape harvest (depending on maturity and temperature conditions) or the adoption of new rules, for example regarding irrigation, can be decisive. Localisation strategies are also an integral part of adaptation. They can benefit from soil and climate heterogeneity within the region. They can also lead to the consideration of relocating vineyards on more important geographic scales (Hannah *et al.*, 2013).

Technical, organisational and localisation changes fall within **institutional transformations and cognitive processes**, which wine cultivators can leverage by means of collective or political actions. As wine cultivation practices and vineyard localisation are regulated through a system of geographic indications, the development of that system becomes a powerful lever in implementing and guiding adaptation. Behind these changes, the development of new expertise and capabilities for action are being affected. Training, access to information, public and private investment in R&D, and development of cooperative ties between wine-growers and researchers are thus levers of adaptation, just as the development of consumer knowledge and preference are in the wine market.

Many solutions therefore exist. However, the true question when choosing which responses to adopt is the consideration of which changes would be considered 'acceptable'. Changing the grape variety, relocating the vineyards, and even changing the economic model and abandoning wine cultivation can all be considered, or rejected, as measures of adaptation, depending on the point of view. Naturally, the larger the definition of adaptation is, the greater the number of levers that come into play, and the easier adaptation will be. One extreme case arises when the choice is between adaptation 'at the margins', which endorses all possible responses to maintain things as they are, and 'bifurcation' towards new activities or new locations. For example, this question is pressing for ski resorts at low and medium altitude, which risk being unable to offer ski services in the future (Hallegatte *et al.*, 2011). It is also at the heart of issues facing traditional wine-growing regions and future wine-growing regions (Hannah *et al.*, 2013).

Selecting the right action, or program of action, is not easy. This require to identify the costs and the benefits. Both of them can be difficult to assess, as they do not only include a financial dimension, but also cultural and social ones. It should also not be forgotten that every climate adaptation policy carries, on the one hand, costs, and, on the other hand, residual impacts of climate change, that is to say, impacts that will remain after the adaptation measures have been applied. The choice between different adaptation policies, and between adaptations 'at the margins' and 'bifurcations', in particular, is made by weighing both sides of the question.

IN THE FACE OF UNCERTAINTY AND IRREVERSIBILITY, HOW CAN MEASURES FOR ADAPTATION BE CHOSEN ?

A certain number of general problems, however, make this analysis extremely difficult.

Firstly, the climate is continuously changing. Consequently, the objective is not to be perfectly adapted to the predicted climate of 2050 or 2100, but to be adapted to a ceaseless change. Wine-making practices, and more broadly, value chain organisation, cannot change overnight. The aim for the coming century is to succeed in keeping pace with climate change. We must therefore be careful that the adaptation measures that are effective for moderate warming will not constrain future action or have negative consequences in the long-term, when warming will be greater. For example, the establishment of a vineyard dependant on an irrigation system can hit a wall if the source of water is itself threatened by the change in climate. Also, massive replanting of a variety of vine that is known to reach fruition later but that does not have re-enforced resistance against summer dryness could prove to be catastrophic. These examples are under the title 'mal-adaptation', i.e., adaptation measures that exacerbate, rather than reduce, vulnerability (IPCC, 2007).

A second difficulty is the fact that it is not known precisely what the future climate will be. This uncertainty has two very different origins : our incomplete knowledge of climate on the one hand, and, on the other, the inability to predict exactly what GHG emissions will be in the future. These uncertainties in climatic projections increase as we consider local scales or intra-annual variation in temperature and rainfall, which is crucial to wine cultivation and quality. A comparison between Figures 1 and 2 gives a good idea of the uncertainty caused by our incomplete knowledge of the climate ; it shows two different projections from two different climate models of the same emission scenario.

Faced with these uncertainties, how should methods of adaptation be chosen ? Should they be radical or at the margins ? How can a decision be made for an investment that will take many decades to pay off ? One solution is to err on the side of caution and systematically consider the worst-case scenario. This solution makes sense but is difficult to apply in practice because the costs are often extremely high and there is the risk of paying too high a price for a result that does not justify it.

A more flexible approach involves limiting the number of possible scenarios to those in which the situation is considered unacceptable (Lempert and Collins, 2007 ; Hallegatte *et al.*, 2011), the 'unacceptable' standard being defined by a political decision. This approach identifies uncertainty and puts robust measures in place to address it (Hallegatte, 2009). Indeed, measures exist that are positive in a great number of scenarios, including the most extreme cases, and incur only very moderate costs in the other scenarios (Barnett, 2001 ; Heltberg *et al.*, 2009 ; Wilby and Dessai, 2010). Two important categories of such measures can be highlighted : 'no regrets' measures and 'reversible and flexible' measures.

'NO REGRETS' MEASURES

A first approach works with the fact that we are not perfectly adapted to our current climate and are already vulnerable to a certain number of environmental problems : biodiversity is threatened by the consequences of numerous human activities, water is frequently consumed in a non-sustainable fashion, and a significant percentage of the population lives in flood risk areas. Projected climate change consequences will, in many cases, be a worsening of these already existing problems ; for example, water resources will likely diminish in areas where they are now misused, and the frequency of floods will increase in a certain number of areas that are already prone to flooding.

Consequently, one effective adaptation measure is to start managing the current situation better. This is what is called a 'no regrets' measure, that is to say, the co-benefits themselves justify putting the measures in place, and thus the impact will be positive, irrespective of the envisaged scenario. These measures are not easy to put in place (if they were, it would have been done already) and do not allow for adaptation to all the impacts of climate change, but they constitute an effective first step. In the case of wine cultivation, an investment in technology that will help reduce alcohol content could fit into this category, at least in the case of the standard wines from Mediterranean Europe. An increase in the percentage of alcohol is in fact already penalised in many markets, and being able to reduce alcohol content can increase the saleability of wines in these markets as well as anticipate a trend that will continue. Even those actions aimed at preserving the soil and increasing its level of organic matter are likely to have quite rapid beneficial effects on the vine and re-enforce the image of wine as a natural product, while limiting the effects of more sporadic rainfall.

Another example of measure consists in investing, when the opportunity presents itself, in security margins. In some cases, the cost of adapting to worst scenarios, or at least to extreme ones, is not very high. It can therefore be useful to do it. Agronomic practices and landscaping that can limit erosion under heavy rain events illustrates this. In the case of an overestimation of the impacts of climate change, the cost would not be high, but the gain might be considerable (Hallegatte, 2009).

'FLEXIBLE AND REVERSIBLE' MEASURES

In the face of any change, the great challenge is the management of inertia. We are vulnerable to climate change if we do not succeed in adapting ourselves at the same pace. A second approach gives preference to measures that limit this inertia and that can be adjusted or cancelled when new information becomes available, or in other words, flexible or reversible measures.

This could take the form, for example, of reducing the length of the investment period and trying, as far as possible, to avoid long-term investments. An investment that is expected to be profitable in 10 years will in fact be less affected by the diverse possible changes in climate than an investment that is expected to be profitable in 20 years or more. In the first case, it is possible to take into account how climate has actually evolved during the first 10 years and design the next 10-year investment accordingly. This would be impossible in the second case.

In the field of wine cultivation, a parallel can be made between the amortisation period of a plantation and the choice of oenological equipment, or irrigation, for which there are different technological options that are deployable to a greater or lesser extent. As one of the characteristics of climate change is also the escalation of inter-annual variability and its effects on vintage, the decisions aimed at reducing or endorsing these effects will promote flexibility in wine-growing systems. Investment in diversification of vine varieties, as well as wine-making techniques and the wines themselves, increases the range of options, experiments and possible blends, in spite of vicissitudes in climate and in the market.

Another type of 'flexible measure' is to favour the use, whenever possible, of reversible strategies, such as financial or institutional adaptation strategies, over investments in costly technological solutions. Such strategies can indeed be adapted, changed or cancelled at low cost and almost no money lost, whereas in the case of a costly investment, turning back means that the money invested is lost. Illustrative examples come from different fields outside viticulture, such as for instance the increased risk of flooding in many areas due to climate change. It is possible to protect against flood risk, either by restricting land-use plans and banning development in future potential flood risk areas, or by constructing flood defences (dykes) (Hansen *et al.*, 2011). The big advantage of the first solution is that land-use plans can be modified if the risk factor has been overestimated, whereas once an oversized dyke has been built, the money is lost.

CONCLUSION

Over and above technological and agronomic problems, the conception and selection of adaptation measures to climate change raise specific difficulties :

- Climate change is an evolving process : knowing how to adapt to a new climate is not enough, we need to know how to adapt to a climate that is continually changing ;
- The exact characteristics of the future climate are not known with great precision, partly because it is not possible to predict what our future GHG emissions will be, and partly because its expression at local scale, so critical to viticulture, is subject to multiple parameters which interact with each other ;
- The indirect effects of climate change on the resources and ecosystems that condition an activity add another level of uncertainty. For example, in viticulture this applies to water supply and to pests and diseases ;
- Political, institutional and even cultural conditions for vine adaptation are wide open and do not only encompass innovation or delocalisation but also the development of consumer preferences.

Adaptation strategies to climate change must explicitly take into account these difficulties. That does not, however, make the task impossible. A number of robust strategies for planning ahead exist, robust enough to take on the continuing changes in climate as well as the range of possibilities for the climate of tomorrow. All these measures come at a price in the short term, and it is not simple to put them in place. Thus, amongst the measures that we have listed, reducing the duration of the lifespan of investments generally leads to less profitable choices of investments. Investing at the margins of security is not free and does not come with short-term gains. Reversible strategies are less easy to put in place or to enforce. The cost, however, should be seen as an insurance which you pay initially, but which limits the possibility of future losses.

Because of the time-scale of climate change, it is unfortunately more and more difficult to have feedback and to learn from experience, and so we are forced to anticipate (Hallegatte *et al.*, 2011). Waiting to see which adaptation strategies have worked elsewhere increases the risk of acting too late. Research and long-term planning, the exchange of ideas, and collaborations between actors can, however, facilitate the process. For wine cultivation, two important lines of approach can direct the desired cooperation between scientists, wine-growers and political decision-makers: firstly, continue studying and comparing the great diversity of current wine-producing systems as well as the existing genetic resources that have resulted from the historic adaptation of viticulture in different climates, as this diversity will in all probability cover the situations expected from now until the end of the 21st century, and secondly, conceive and experiment with more radical options, including biotechnologies and agro-ecological and social innovations. The history of vine and wine is precisely one of a series of innovations that are part of the technological and cultural evolution of societies.

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

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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

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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.

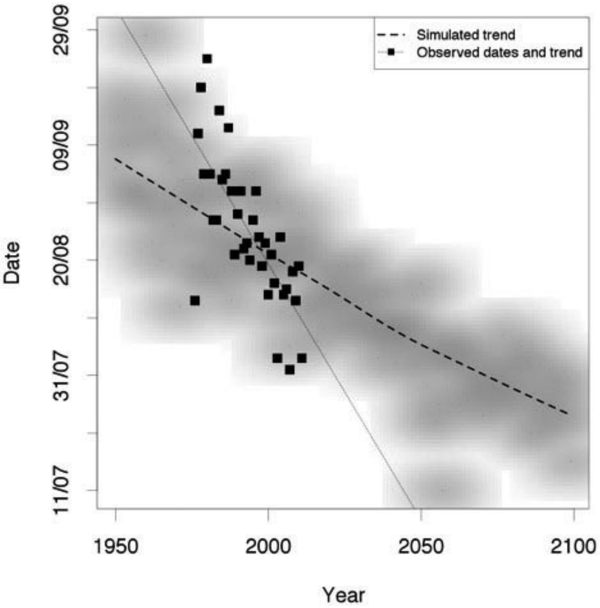

Figure 1 - Observed (black squares) and density cloud of simulated veraison dates for Riesling in Colmar. A1B scenario, MétéoFrance ARPEGE-Climat model, Weather type (WT) downscaling method.

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.

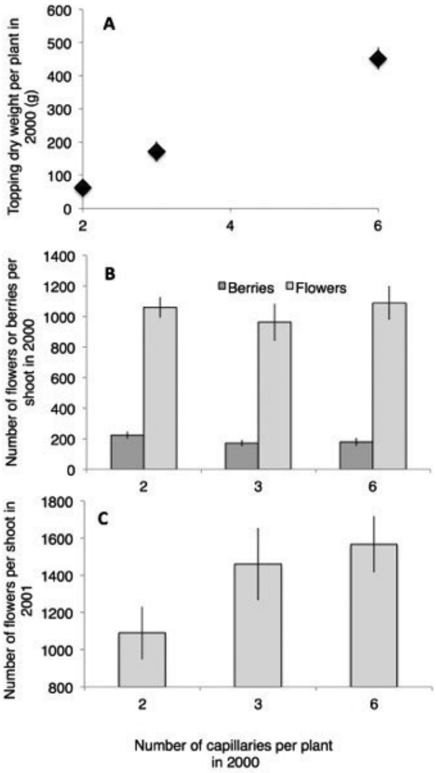

Figure 2 - Greenhouse experiment with Grenache grown in 80-l containers. Two, three or six capillaries were left for water supply one week before flowering in 2000. The same containers were well watered in 2001. (A) Total biomass dry weight removed from the plants above the stalks in 2000. (B) Number 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

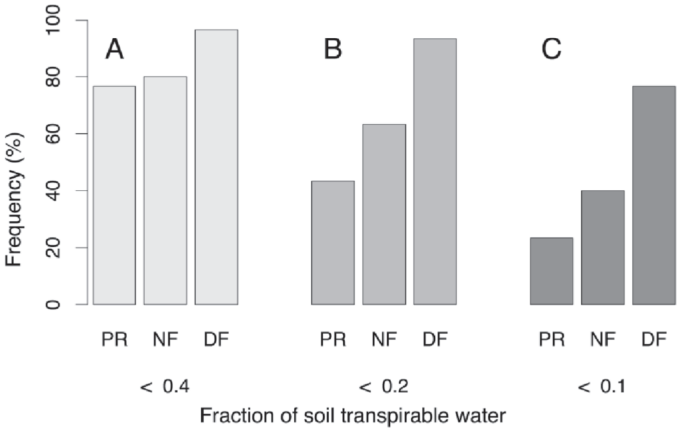

Figure 3 - Frequency of years with moderate (A), severe (B) and very severe drought stress (C) during the 35 days after veraison.
Riesling, A1B scenario for Colmar, Quantile-Quantile (QQ) downscaling method. PR: present 1975-2005, NF: near future 2020-2050, and DF: distant future 2070-2100.

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

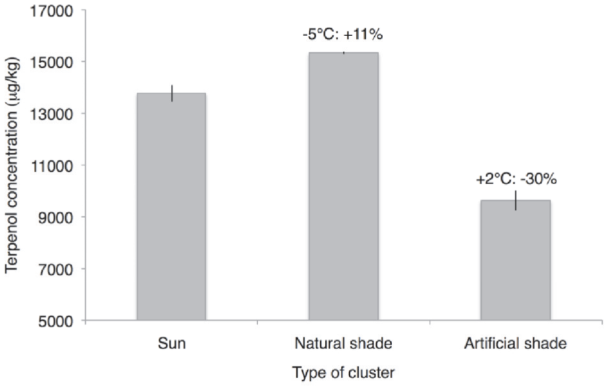

Figure 4 - Terpenol content of Muscat de Frontignan berries according to the type of cluster.
Data from Bureau *et al.*, 2000, year 1996.
Bars represent standard errors. Data above the bars are differences with the control "sun" treatment.

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).

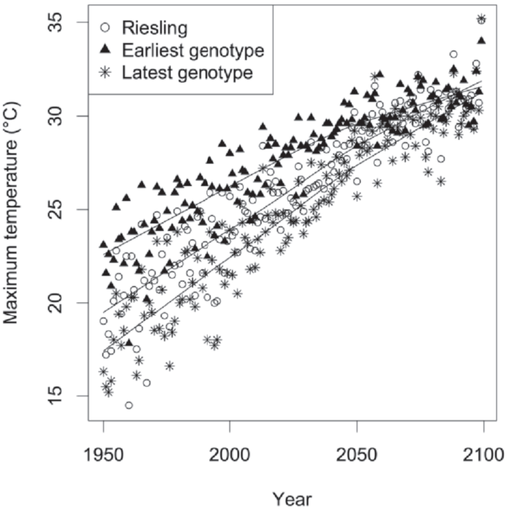

Figure 5 - Average maximum temperatures in Colmar during the 35 days following veraison for three genotypes. Empty circles: Riesling, Black triangles and stars: genotypes with the earliest and latest veraison dates, respectively, that we can imagine to breed from a Riesling x Gewurztraminer cross. A1B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

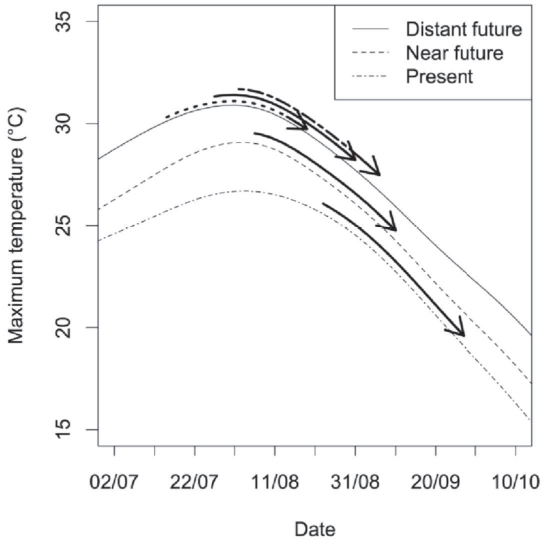

Figure 6 - Daily maximum temperatures averaged for three periods in Colmar: present (1975-2005), near future (2020-2050) and distant future (2070-2100). The plain arrows represent the corresponding ripening periods for Riesling. The dotted and dashed arrows represent the ripening periods in the distant 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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ADAPTING RED WINEMAKING TO CLIMATE CHANGE CONDITIONS

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Abstract

Aims: The general aim of this article is to explore the negative effects of climatic change on grape ripening, how it affects red wine composition and quality, and how we can mitigate these problems by applying some technical procedures in the winery.

Results: Specifically, global warming induces an increasing unbalance between primary and secondary metabolism of vines. This phenomenon causes grapes to rapidly reach very high sugar content, very low acidity and very high pH. This forces grapegrowers to harvest the grapes before reaching the correct skin and seed maturity, which seriously affects seriously the wine composition and quality.

Conclusion: This new scenario represents a new challenge for the wine industry, which needs to develop new strategies for better winemaking. Different possibilities such as accelerating anthocyanin extraction, eliminating seeds, employing lees or inactive yeasts to enrich the wine in polysaccharides, and applying techniques directed to partial dealcoholization of wines and/or to decrease in wine pH are discussed.

Key words: climate change, grape maturity, winemaking

Résumé

Objectifs : L'objectif général de cet article est d'explorer les effets négatifs du changement climatique sur la maturation du raisin, la façon dont il affecte la composition du vin rouge et sa qualité et comment nous pouvons atténuer ces problèmes en utilisant de nouvelles techniques dans le chai.

Résultats : Le réchauffement climatique provoque une augmentation du déséquilibre entre le métabolisme primaire et secondaire de la vigne. Ce phénomène fait que les raisins atteignent rapidement une teneur en sucre très élevée, une acidité très faible et un pH très élevé. Cela force les producteurs à récolter les raisins avant d'atteindre la maturité correcte dans les pellicules et les pépins, ce qui affecte sérieusement la composition du vin et sa qualité.

Conclusion : Ce nouveau scénario représente un nouvel enjeu pour l'industrie du vin qui a besoin de développer de nouvelles stratégies pour une meilleure vinification. Différentes possibilités telles que l'extraction plus rapide des anthocyanes, l'élimination des pépins, l'emploi de lies ou des levures inactives pour enrichir le vin en polysaccharides et l'utilisation de techniques pour désalcooliser partiellement et / ou pour diminuer le pH du vin sont discutées.

Mots clés : changement climatique, maturité du raisin, vinification

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The concept of climate change is not new. In fact, many years ago it was described by some scientists, who were then dismissed as alarmists. Today, everybody knows that the consumption of fossil fuels is causing an increase in the concentration of carbon dioxide and other gases, which, by reflecting the radiation backoff to earth, are causing a greenhouse effect (Crowley, 2000; Zamora, 2005a) that is responsible for the current global warming of the planet. Data are truly frightening. In 1958, the atmospheric concentration of CO_2 was 315 ppm. Today, it is more than 370 ppm, and in the best case scenario, it will be higher than 500 ppm by the end of the twenty-first century (IPCC, 2012).

But what impact will climate change have on viticulture? Figure 1 synthesizes the major effects of climate change on the grape ripening process. Basically, global warming leads to a faster accumulation of sugars and a faster degradation of acids in grapes compared to normal conditions (Jones *et al.*, 2005; Mira de Orduña, 2010). Therefore, grapes reach very high potential alcoholic degree and pH sooner than usual. This phenomenon causes the advance of the harvest date. However, skins and especially seeds remain already unripe. Therefore, an increasing imbalance between technological and phenolic maturity takes place as a consequence of climatic change. In these conditions, when grapes are not well-ripe, the winemaker has a very difficult decision to make. If he carries out a short maceration, the wines will not have enough colour. On the contrary, if he carries out an extended maceration, the risk of extracting astringent, herbaceous and bitter tannins is really very high (Llaudy *et al.*, 2008).

What can the oenologist do in that situation? I think that there are only two possibilities. First, harvest when alcoholic degree and/or pH are at the correct level and then adapt winemaking to conditions of unripe grapes. Second, wait for complete maturity and harvest when grapes are fully ripe, and then apply techniques for decreasing the alcoholic degree and pH (Zamora, 2007).

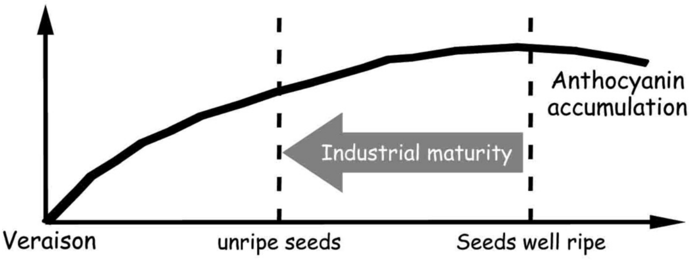

Figure 1 - Effects of global warming on grape maturity

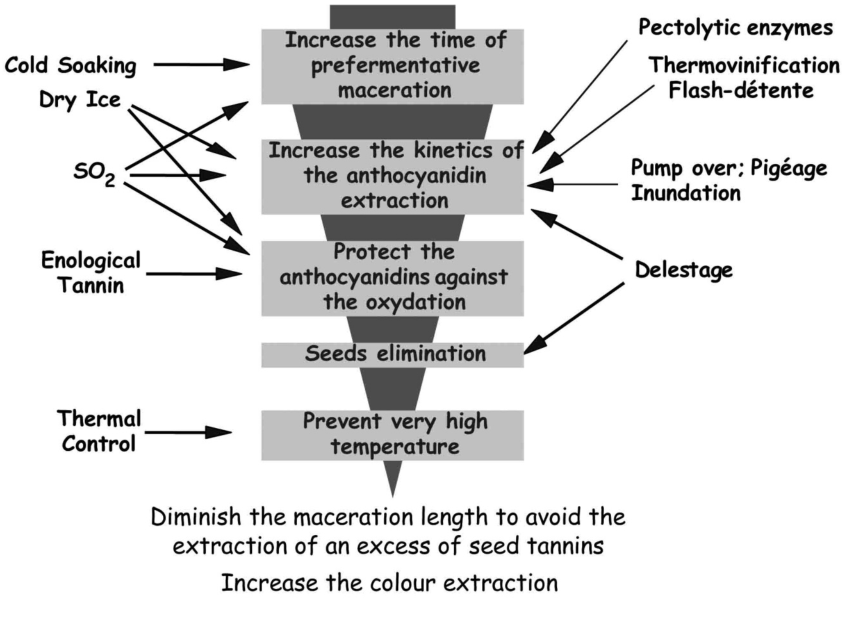

Figure 2 - Possible winemaking strategies to apply when the grapes are not ripe enough

In the first case, there are different possible strategies for winemaking unripe grapes. Figure 2 illustrates some of the different possibilities. Basically, maceration time must be shortened to avoid the extraction of excess seed tannins and simultaneously colour extraction must be accelerated. To achieve this, the time of the pre-fermentative maceration can be lengthened by means of a cold soaking (Zamora, 2004; Llaudy *et al.*, 2005). Anthocyanins can be protected against oxidation by the use of carbon dioxide, sulphur dioxide or even oenological tannins (Zamora, 2003a). The kinetics of anthocyanin dissolution can be increased by means of a pectolytic enzyme treatment (Guadalupe *et al.*, 2007), a thermal treatment or an increased mechanical treatment of the cap (pump over, *pigeage*, inundation or *délestage*) (Zamora, 2003b).

Another interesting strategy to be applied when the grapes are not ripe enough may be the elimination of the seeds, which can be carried out by means of *délestage* (Zamora, 2005b). Figure 3 illustrates the effects of eliminating and adding seeds on red wine parameters (Canals *et al.*, 2008). The elimination of seeds by *délestage* can produce a slight decrease in red colour intensity and total phenolic concentration. However, it also drastically decreases astringency, making the wine more pleasant. This smoothing of wine astringency is mainly due to the reduction of epicatechin gallate present in seed tannins.

Finally, once alcoholic fermentation is finished, other possible strategies can be employed if the wines are too astringent or bitter. An appropriate microoxygenation or oak ageing can be very useful for smoothing unripe tannins (Llaudy *et al.*, 2006). On the other hand, the wine's body can be increased and astringency smoothed by enriching the wine with polysaccharides by means of ageing the wine with lees (Zamora, 2002; Rodríguez *et al.*, 2005), by employing yeast strains with higher polysaccharides production (Gonzalez-Ramos and Gonzalez, 2006) or by supplementing the wines with inactive yeast specifically pre-treated to increase the release of polysaccharides (Guadalupe *et al.*, 2007; Rodriguez-Bencomo *et al.*, 2010).

As aforementioned, the other possibility is to wait for the complete maturity and harvest the grapes fully ripe, and then apply techniques for decreasing the alcoholic degree and pH. Here are the possible strategies to correct a high alcoholic degree and a high pH are presented now:

- Selection of cultivars and clones that ripen later (Schultz, 2000).
- Adaptating farming practices to this new situation (Schultz, 2000).
- Selection of yeasts with lower yield of sugar/ethanol transformation (Dequin and Barre, 1994).

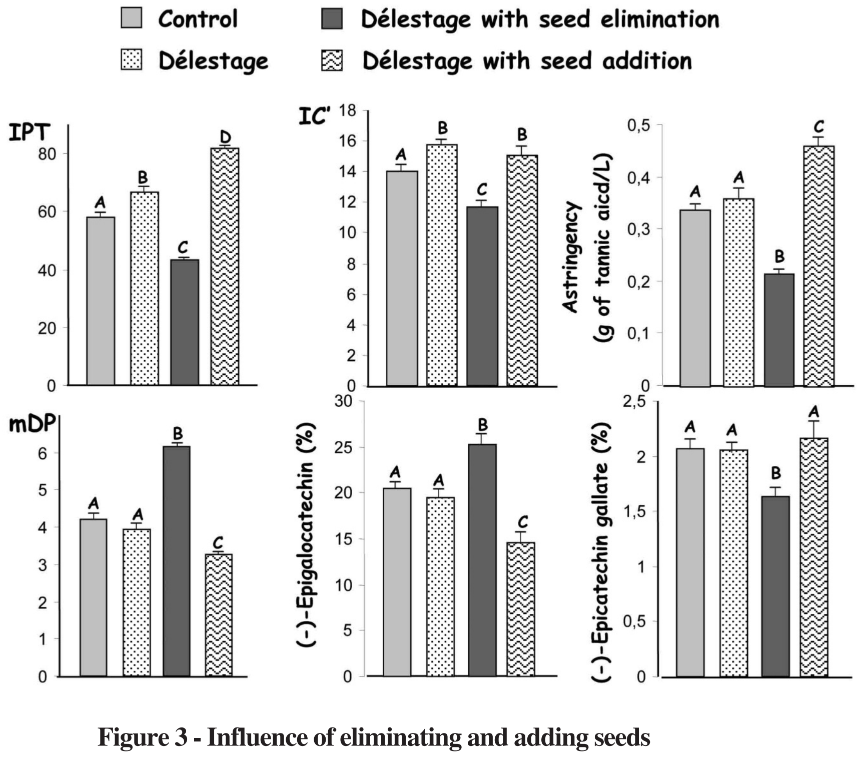

Figure 3 - Influence of eliminating and adding seeds

- Decreasing the content of sugars in grape juice or ethanol in wine by reverse osmosis (Estévez *et al.*, 2011).

- Partial evaporation of ethanol from wine (Takács *et al.*, 2007).

- Reduction of pH: cationic exchange and electrodialysis (Walker *et al.*, 2004).

- Use of unripe grapes harvested during cluster thinning as a method for reducing alcohol content and pH of wine (Kontoudakis *et al.*, 2011).

The first two points are probably the best strategies. It is clear that using new clones or cultivars, modifying farming practices and even moving vineyards to other production areas makes it possible to delay berry sugar accumulation and acid consumption (Schultz, 2000). It should be taken into account that much work on clonal selection in recent years has been aimed at obtaining grapevines that can quickly produce high sugar content. Now we need to retrace our steps and search for the old vines that are better adapted to the new climatice conditions. However, these strategies require long and laborious studies and a considerable economic investment to replant most of the vineyards.

The use of yeast with a lower ethanol production yield has also been proposed. However, it seems that natural *Saccharomyces cerevisiae* strains always achieve similar ethanol yields, which leads to an impasse unless genetically modified organisms (Dequin and Barre, 1994; Malherbe *et al.*, 2003) or non-*Saccharomyces* yeasts are used (Ciani and Ferraro, 1996).

The strategies 4-7 are now better known, although a lot of work is necessary to improve their efficiency and applications. Among these techniques, reverse osmosis is probably the most used worldwide. This technique is now a reality and some companies even offer wineries the possibility of renting this equipment. Table 1 shows an experimental assay of partial dealcoholization by reverse osmosis with two red wines fromof AOC Priorat and AOC Penedès (Estévez *et al.*, 2011).

The results showed that significant differences were found only in alcohol content, while the other laboratory parameters remained unchanged. These wines were also tasted by a trained sensory panel using the discrimination triangular test. In general, tasters were able to distinguish between the control and the partially dealcoholized wines, but they all confessed that it was quite much harder than expected. Therefore, it seems that reverse osmosis can be a useful procedure to compensate the excess of ethanol in wines.

Finally, another possible strategy is the use of unripe grapes harvested during cluster thinning as a method for reducing the alcohol content and pH of wine. Kontoudakis *et al.* (2011) have shown that grapes from cluster thinning can be used to produce a very acidic, low-alcohol wine. This wine can then be then treated with high doses of charcoal and bentonite. The resulting odourless and colourless wine can be used to reduce pH and ethanol content of wine produced from very ripe grapes, that have reached complete phenolic maturity. In their study, the authors have employed grapes of *Vitis vinifera* cv. Cabernet-Sauvignon and Merlot from AOC Penedès and Bobal from the AOC

Table 1. Partial dealcoholoization by reverse osmosis

Parameter	AOC Penedès			AOC Priorat		
	Control	-1%	-2%	Control	-1%	-2%
Ethanol content (%)	14.8 ± 0.2 A	13.8 ± 0.2 B	12.8 ± 0.2 C	16.2 ± 0.2 A	15.1 ± 0.2 B	14.1 ± 0.1 C
Titratable acidity (g/l)	4.8 ± 0.1 A	4.8 ± 0.1 A	4.9 ± 0.1 A	5.2 ± 0.1 A	5.2 ± 0.1 A	5.6 ± 0.1 B
Color intensity	15.3 ± 1.5 A	15.6 ± 0.9 A	15.4 ± 0.7 A	15.4 ± 0.2 A	15.2 ± 0.4 A	14.5 ± 0.5 A
Hue	67.7 ± 1.1 A	67.9 ± 0.4 A	68.3 ± 1.5 A	59.3 ± 1.2 A	60.0 ± 0.4 A	59.2 ± 0.5 A
Anthocyanins (mg/l)	567 ± 41 A	546 ± 19 A	574 ± 14 A	200 ± 13 A	206 ± 23 A	226 ± 11 A
IPT	72.9 ± 2.5 A	73.9 ± 2.3 A	75.8 ± 20.6 A	62.4 ± 0.5 A	62.2 ± 0.2 A	62.1 ± 0.8 A
Proanthocyanidins (g/l)	1.8 ± 0.3 A	1.6 ± 0.2 A	1.7 ± 0.2 A	1.6 ± 0.2 A	1.7 ± 0.3 A	1.5 ± 0.2 A
mDP	6.8 ± 1.2 A	7.5 ± 1.8 A	7.2 ± 0.6 A	6.8 ± 1.8 A	5.8 ± 0.3 A	6.5 ± 0.7 A

All data are expressed as the average of the three replicates standard deviation (n = 3). Statistical analysis: one-factor ANOVA and Scheffe's test (both p<0.05). Different letters indicate the existence of statistically significant differences.

Table 2. Influence of partial dealcoholization by using grapes from cluster thinning

Parameter	First harvest	Second Harvest	
		Control	Dealcoholized
Ethanol (%)	13.4 ± 0.1 ***A***	15.9 ± 0.1 ***B***	14.2 ± 0.1 ***C***
TA (g/L)	7.0 ± 0.2 ***A***	6.3 ± 0.2 ***B***	7.1 ± 0.1 ***A***
pH	3.45 ± 0.01 ***A***	3.76 ± 0.03 ***B***	3.55 ± 0.07 ***C***
Anthocyanidins (mg/L)	191 ± 20 ***A***	252 ± 25 ***B***	271 ± 5 ***B***
Color Intensity	8.7 ± 0.9 ***A***	12.6 ± 1.5 ***B***	17.0 ± 1.9 ***C***
Proanthocyanidins (mg/L)	427 ± 115 ***A***	1070 ± 17 ***B***	969 ± 41 ***C***
mDP	2.72 ± 0.13 ***A***	4.80 ± 1.84 ***B***	4.43 ± 0.36 ***B***
(+)-Catechin (%)	26.2 ± 2.2 ***A***	21,8 ± 1.4 ***B***	19 ± 2.1 ***B***
(-)-Epicatechin (%)	57.8 ± 0.7 ***A***	57.6 ± 0.1 ***A***	57.6 ± 1.9 ***A***
(-)-Epicatechin-3-O-Gallate (%)	4.4 ± 0.4 ***A***	4.9 ± 0.2 ***B***	5.7 ± 0.3 ***C***
(-)-Epigallocatechin (%)	11.6 ± 1.3 ***A***	16.5 ± 0.6 ***B***	17.7 ± 0.7 ***C***

All data are expressed as the average of the three replicates standard deviation ($n = 3$). Statistical analysis: one-factor ANOVA and Scheffe's test (both $p<0.05$). Different letters indicate the existence of statistically significant differences.

Utiel-Requena., The grapes were harvested at two different ripening stages: the first harvest was carried out when the degree of potential alcohol was between 13.0 and 14.0 %. and the second harvest was carried out when the grapes had reached optimum phenolic maturity. Three tanks from the first harvest and three tanks from the second harvest were elaborated without any addition of the low-ethanol wine. Three other tanks from the second harvest were used for the alcohol-reduction experiment. Specifically, a portion of the total volume of the grape juice was removed and replaced with the same volume of low-alcohol wine. Table 2 shows the analytical parameters of the obtained Merlot wines. Similar results were obtained in wines from the other two cultivars.

As expected, the wines, in which part of the juice had been replaced by the low-alcohol wine, had a lower ethanol content and pH than their corresponding controls. In fact, the ethanol content, the pH and the titratable acidity of these wines were closer to the control wines of the first harvest than to those of the second harvest for the three cultivars. The results concerning phenolic compounds and colour were very clear. In fact, the anthocyanin and proanthocyanidin concentrations as well as the proanthocyanidin mean degree of polymerization (mDP) and the percentage of (-)-epigallocatechin of wines from the second harvest were significantly higher than those of the first harvest. These data confirm the great influence of phenolic maturity on these parameters. On the other hand, the values of all the treated wines were similar to those of the control wine of the second harvest. Furthermore, since the pH of the treated wines was significantly lower than that of the non-treated wines, their colour intensity was considerably higher.

It can be concluded that the proposed technique may be useful for the partial reduction of alcohol content and the simultaneous decrease of pH of wines. The colour of the reduced-alcohol wines was better than that of their corresponding controls and their phenolic composition was similar. Moreover, this procedure does not require additional equipment and is easy to apply in standard wineries. Further experimentation is needed to better adapt the process in order to obtain more balanced wines without the problems of excess alcohol and high pH.

The climate change is inevitable. We can only can adapt to it and try to mitigate its effects. These techniques are now available and can be very useful to compensate the effects of global warming in our wineries. Nevertheless, global warming is a major problem and, evidently, the real solution is elsewhere. Fifty years ago, on 12 April 1961, Yuri Gagarin became the first human to travel into space. He was therefore the first human to see the earth from space. In front of this magnificent landscape, he made this historical statement : "Orbiting Earth in the spaceship, I saw how beautiful our planet is. People, let us preserve and increase this beauty, not destroy it".

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IMPACTS AND ADAPTATION TO CLIMATE CHANGE : NEW CHALLENGES FOR THE FRENCH WINE INDUSTRY

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Abstract

Climate change will impact vine growing in France and the quality of wines in any regions. We summarized here the main information provided throughout the different contributions to this special issue. We attempted to draw some general conclusions in terms of adaptation strategies and to show how the interactions developed between scientists and actors as part of the LACCAVE project can contribute to fulfill the expectations of the French wine industry for the future.

Key words : climate change, grape growing, wine making, adaptation, perception, impact studies

Résumé

Le changement climatique aura des effets sur la culture de la vigne en France et affectera la qualité des vins produits dans toutes les régions. Nous synthétisons ici les enseignements des différentes contributions à ce numéro spécial. Nous tentons également de tracer des directions en termes de stratégies d'adaptation et essayons de montrer comment les interactions développées entre scientifiques et acteurs dans le cadre du projet LACCAVE peuvent contribuer à répondre aux attentes de la filière viti-vinicole française pour l'avenir.

Mots clés : changement climatique, viticulture, œnologie, adaptation, perception, études d'impact

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According to the Vth Intergovernmental Panel on Climate Change report, recently released, climate change over the last decades is unequivocal and will continue for the following century (IPCC, 2013). In Northern hemisphere, the last 30 years were the warmest of the last 1400 years. Human activities have largely contributed to this global warming. The increase in average surface temperature by the end of the XXIst century is predicted to be likely over 1,5 °C in all the scenarios and up to 4,8 °C in the most extreme scenario 8.5 (atmospheric [CO_2] of about 1700 ppm). The Artic regions and lands will warm up quicker than other regions and oceans. Precipitations will be affected with a larger range between dry and wet regions and dry and wet seasons. Sea level will likely increase from 0.26 to 1 m in the most extreme scenario.

As stated by all the contributors to this special issue of the *Journal International des Sciences de la Vigne et du Vin* (JISVV), these changes will impact vine growing in France and the quality of wines produced in any regions. Consequently, adaptation defined as "*the set of organization, localization and technical changes that societies will have to implement to limit the negative effects of climate change and to maximize the beneficial ones the set of organization, localization and technical changes that societies will have to implement to limit the negative effects of climate change and to maximize the beneficial ones*" is a necessity (Hallegatte *et al.*, 2011). The main goal of adaptation strategies, as expressed by representatives of the wine industry, is to maintain yield potential and wine typicity at a regional level. To reach this goal, most actors of the wine industry, including scientists, first think of "technical solutions", such as oenological methods, cultural practices or plant material. Because of the diversity in growing conditions and wine making processes around the world, many of these potential innovations are already used elsewhere. They only need to be exchanged between actors, then experimented and adapted to French vineyards (Tonietto *et al.*, 2014). Consequently, technical changes may not be a major challenge in the medium-term future. In France, the production, exchange and consumption of wine is heavily regulated by standards, rules and institutions, which monitor the technical innovations in the value chain as well as the location of the vineyards. Thus, institutional changes emerge as very important levers for adaptation to climate change. Economic aspects as well as evolution of consumer preferences will also have significant influences. Scientists and representatives of the wine industry also underline that local and regional levels are crucial for adaptation : on one hand, climate is diverse at interregional and intraregional scales (Quénol and Bonnardot, 2014), making climate change impacts more or less restrictive from one region to another ; on the other hand, production systems and wine characteristics also differ depending on the region and could be more or less sensitive and resilient. Northern regions have relatively more freedom with respect to adaptation in comparison to southern regions where, in the long term, bifurcation towards new systems may be more likely (Viguié *et al.*, 2014). We must also consider that each wine region fosters specific relations between research centers, technical institutes, professional organizations and wine producers, leading to different cooperative strategies, and probably different abilities to adapt.

There is a general agreement that temperature change will increase the earliness of all developmental stages of grapevine by 2-3 weeks to 40 days in the worse scenario. Yield is under the control of several climatic drivers such as atmospheric [CO_2], temperature and water supply. It is likely that yield will be reduced when water will become a limiting factor (Pieri and Lebon, 2014). Fruit composition has and will be further modified with a tendency towards higher sugar content, lower acidity, and modified polyphenol and aroma content. According to the observed correlation between bioclimatic indices and wine attributes, climate warming will probably affect wine quality (Tonietto *et al.*, 2014). The imbalance between primary and secondary metabolisms may increase, which will make the decision about harvest dates more difficult (Zamora, 2014). However, experimental data about the individual effect of climatic drivers on berry secondary metabolism are still scarce and difficult to collect. For example, experiments easily mimic heat waves, but warming over several seasons is much more difficult to assess. Information about the combined effects of climate drivers is almost inexistent. These scientific challenges need to consider not only responses to environmental constraints, but also adaptation mechanisms.

Climate change will not only affect grapevine development but the entire ecosystem and socio-economic system. On the ecosystem side, soil microbial activity and berry microflora will likely be modified. Grapevine diseases are also an important issue. Changes in the epidemiological pattern and geographical distribution of pests and pathogens are expected, but these topics are still very poorly addressed by the scientific community (Caubel *et al.*, 2014). On the socio-economic side, climate change will impact the technical and value chains from vine growers to wine consumers. Direct impacts include the economic costs, incomes and work organization at the farm level, the competitiveness of firms and wine making regions, and conditions of transport and consumption. Indirect impacts, which integrate the consequences of adaptation strategies, will affect both the geographical distribution of vineyards and the institutional framework of the wine industry. Different options will be discussed during the next 30 years, and the labeling system (geographical indications) and market regulation will likely change, at least by taking into account new practices and new (re) locations of vines. As reported by various representatives of the French wine industry, actors should consider different climate change perceptions as well as a variety of adaptation strategies. The impacts of climate change have to be evaluated according to these strategies, which combine innovation, choice of location and institutional change.

Despite ongoing effort to reduce greenhouse gas emissions, adaptation is the only solution. Viticulture and wine processing have existed for more than 2000 years and have proved to be able to adapt to new conditions throughout this period. Consequently, drama is not an issue (Van Leeuwen *et al.*, 2013). The diversity of genetic resources, geographical and climatic conditions, and wine-producing systems is highly important for adaptation and has to be studied and used. However, in order to minimize the negative impacts, the rate of adaptation is a matter of concern. This special issue of JISVV gives an overview of possible technical adaptations for vine growing and wine making processes. Investing in research for improved scion x rootstock x training system less vulnerable to water stress or developing reverse osmosis facilities are "no regret" choices (Duchêne *et al.*, 2014). Oenological practices can be considered as the most flexible adaptation strategy with a short life span, but long-term costs and acceptance have to be considered (Zamora, 2014). Experimenting and planting late ripening varieties are also reversible strategies, because over grafting is always possible. Even if it appears as the most efficient and quickest way to cope with drought, investing in costly irrigation systems could be more hazardous on a long-term scale. Indeed, there are serious evidences that climate change will reduce water availability in regions where water is the major limiting parameter for yield. On a long-term scale, the conception and experimentation of more radical options have to be considered.

Developing scientific approaches to support adaptation processes in the wine industry is a major challenge, which becomes per se a lever for adaptation. It is without any doubt a multidisciplinary work, which starts by building a common view among scientists about the possible futures and the main issues for the wine industry. It has been the first step of the LACCAVE project, leading bio-physicians and social scientists to release a special issue of JISVV. Strong collaborative research needs agreements about targeted climatic scenarios in terms of intensity and timing as well as agreements about strategic adaptation scenarios. Gathering and exchanging data, experimenting and modeling climate and processes at local scale, and confronting and integrating assumptions and explanations have to be strongly supported on a long-term scale. These tasks may be performed in close collaboration between scientists and actors of the wine industry : producers, institutional representatives, teaching and training institutions, sellers, decision-makers, and consumers. The representatives of the French industry clearly expressed that they are concerned about the forthcoming changes. They have already implemented mitigation and adaptation strategies and are familiar with adaptive options. They have already defined their goal, advocating for maintaining, as much as possible, the current productive system and type of wines. Scientists working on adaptation need to explore, compare and assess these actions and projects that are emerging in wine making regions all over the world. On the other hand, actors of the wine industry need references, new solutions, and climate scenarios for impact assessment combined with different options of adaptation. These cross contributions between scientists and actors can be achieved by the implementation of a foresight exercise, such as that programed under the LACCAVE project (Ollat and Touzard, 2014).

All these issues and challenges are clearly the core of the LACCAVE project. Results and recommendations will not be absolute at the end of the project. The objective is to open the path and build a network to carry out this huge and decisive task for the future of the French wine industry. A lot of work remains to be done. This special issue of JISVV has helped us to define the main directions that should be taken.

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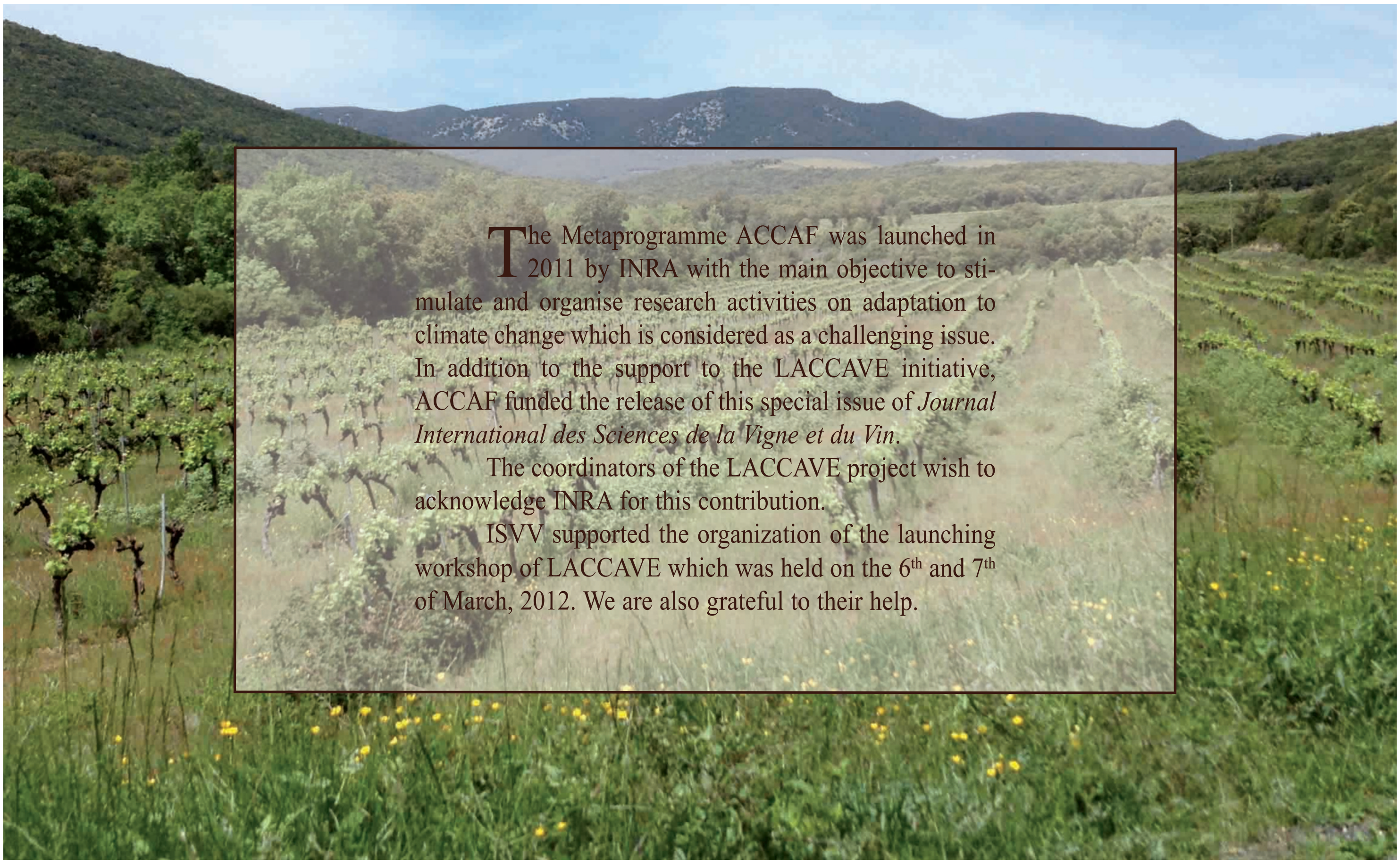

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