Sustainable grape and wine production in the context of climate change

Bordeaux, FRANCE

CLIMWINE 2016 International Symposium

BOOK OF PROCEEDINGS

Nathalie Ollat, Jean-Marc Touzard, Iñaki Garcia de Cortazar Atauri, Hervé Quénol & Cornelis van Leeuwen

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Sustainable grape and wine production in the context of climate change

Book of proceedings

edited by
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In memory of our esteemed colleague Eric Lebon,
an active member of the Laccave team,
deeply involved in climate change studies
and grapevine sciences.
He suddenly passed away in December 2016.

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The challenging issue of climate change for a sustainable grape and wine production

The links between grape production, wine quality, climatic conditions and geographical origins are tied, making ongoing climate change a quite challenging issue for this economical sector. How climatic conditions will be affected locally, how local climate will interact with topography, resulting in a high climatic variability at vineyard scale, how vine performances, berry composition and wine quality will be modifed, what can be done to adapt vine growing and wine making practices to these new conditions ? Here are the numerous questions the wine industry has to face in the following decades. In this context, it is obvious that this issue will require the development of close collaboration between actors, including producers and wine makers, extension services, marketing, policy makers and scientists. In the scientific community itself, addressing this issue requires multidisciplinary studies and new approaches for performing science.

Since 2012, the LACCAVE project, developed in France to study the long term impacts and define adaptation strategies for viticulture and oenology, was based on this vision. It gathers, in the frame of the Metaprogramme ACCAF (Adaptation to climate change of Agriculture and Forestry) led by the French Institut National de Recherche Agraonomique (INRA), scientists from 23 French laboratories dealing with different aspects of climate change: climatology, physiology, pathology, agronomy, oenology, genetics, economics and social sciences. After 4 years working together, they have developed a shared vision about climate change and its impacts on grape and wine production. They also delivered several important results to the industry in order to define adaptive strategies. ClimWine2016, the final international symposium of Laccave project was held in the same spirit. Scientists from 20 different countries came to Bordeaux from April 11 to 13 2016 to present their work related to climate modeling, impacts on vines and wines, possible adaptations at different scales, and socio-economic outputs. This symposium was also an important opportunity not only to exchange among researchers, but also with representatives of the industry.

General trends of already observed and expected climate change and their impacts on grape growing show that the planet is warmer than at any time in our recorded past and extremes in temperature and precipitation have increased (Jones, 2017, in this issue). Most vineyards throughout the world face the same situation and some vineyards from low latitudes as Portugal may be endangered in the following decades (Fraga *et al.*, 2017). Climatic modelling at the appropriate scale is crucial to simulate future conditions (Quenol *et al.*, 2017). In particular, high resolution atmospheric modelling provides useful information to understand climate variability at high spatial and temporal scale and to allow better decision-making for adaptation at the terroir level (Sturman *et al.*, 2017). Water availability will become a major concern. Considering that simulations for precipitations are characterized by a large uncertainty, it is determinant to analyze the evaporative demand of the atmosphere which has so far shown different evolutions according to the considered vineyard. Wind appears to be a key component of these variations (Schultz, 2017). Impacts of climate change on grapevine physiology are numerous. Phenology, driven mainly by temperature, is the first component to be affected and is a key parameter for varietal adaption (Garcia de Cortazar-Atauri *et al.*, 2017). However temperature effects are complex and carbon balance at the whole plant level should be considered (Torregrosa *et al.*, 2017). Interactions with high CO_2 have to be taken into account and impacts of future climatic conditions may be larger than might be predicted from experiments examining factors one by one (Edwards *et al.*, 2017). Fruit composition, especially aroma compounds, is a real matter of concern. These molecules contribute to the typical identity of wines and are highly variable according to climatic conditions and growing practices (Pons *et al.*, 2017). The evolution of pest and diseases is another important issue which is much more difficult to document. Worldwide repartition of diseases does not really help to get clear idea of risk occurrence in the future (Bois *et al.*, 2017). To face these new conditions and ensure the sustainability of the industry, adaption should be considered at every level of the production and value chains. At short term scale, winemaking and oenological practices may contribute to process grapes with higher sugar content and lower acidity (Dequin *et al.*, 2017). At longer time scale, site selection, management practices and plant material selection present a high potential to adapt to the new climatic conditions (van Leeuwen and Destrac, 2017). Looking at the past to understand the future may be very informative and some traditional technics abandoned recently may have a high adaptive potential (Santesteban *et al.*, 2017). A major challenge will be to adapt plant material to these new conditions because adaption is a very complex trait. New approaches, as ecophysiological modelling, should be encouraged (Vivin *et al.*, 2017). For example, these approaches appear to be very promising to develop new varieties and rootstocks better adapted to drought (Simmoneau *et al.*, 2017).

This special issue of OENO One, which includes some of the key contributions to ClimWine2016 symposium, provides a large overview of the most recent knowledge related to the challenge of facing climate change. It is therefore a unique document to support our global thinking to maintain the performances of the wine industry in the future. The ClimWine2016 convenors deeply thank OENO One for the possibility to make these articles easily accessible to researchers worldwide and to people working in the wine productionsector.

Nathalie Ollat, Inaki Garcia de Cortazar-Atauri, Jean-Marc Touzard
Convenors of the ClimWine2016 symposium
December 2016

LIFE-ADVICLIM project :
ADapatation of VIticulture to CLIMate change :
High resolution observations of adaptation scenarii for viticulture

The LIFE-ADVICLIM project corresponds to the application and demonstration of several years of Research & Development on the impact of climate change in vineyards. Through the previous projects, expertise was built up in the assessment of climate variability inside winegrowing areas. This expertise is being used/applied in the ADVICLIM project to monitor the spatial climatic variability in 6 pilot sites under different environmental conditions for viticulture: i.e. the Bordeaux region (France), Loire Valley (France), Rüdesheim (Rheingau, Germany), Rock Lodge East Sussex (UK), Cotnari (Romania) and Navarra (Spain).

LIFE-ADVICLIM aims to improve local management of vineyards in the face of climate change. It will develop tools to measure and model both contributions to climate change and the impact of climate change. It will build on these to help identify the best responses to mitigate and adapt to the impact of climate change in vineyards.

http://www.adviclim.eu/fr/

Adaptation of viticulture and other agricultural activities to climate change: Current challenges and perspectives for the INRA AAFCC metaprogramme

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Abstract

The metaprogramme on Adaptation of Agriculture and Forests to Climate Change (AAFCC) was launched by the French Institute for Agricultural Research (INRA) in 2011. It aims at coordinating, promoting and integrating multidisciplinary research activities to overcome the scientific and societal barriers that could restrict adaptation. Favouring dialogue between disciplines, AAFCC provides a framework for various projects on adaptation of agriculture and forests to climate change. The strategy focuses on multidisciplinarity and on the implementation of integrated approaches at the sector or territorial level. The issues and general objectives of AAFCC can globally be ordered according to the response time of the systems, from short- to long-term, and the intensity and 'active' nature of adaptation. So far, AAFCC has supported more than 30 research projects and networks, including the LACCAVE and PERPHECLIM projects. After a brief review of the current and forecasted impacts of climate change on agriculture and of the main issues associated with the adaptation of agriculture to climate change, a general overview of the objectives and challenges addressed by AAFCC is presented. Key perspectives that were addressed during the ClimWine 2016 Symposium are presented and discussed in a concluding part.

Keywords: Adaptation to climate change, multidisciplinarity, framework, research support.

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Introduction

Agriculture is highly exposed to climate change, as farming activities directly depend on climatic conditions (European Commission, 2015). Three phenomena are mainly involved: (i) change in rainfall, (ii) rising temperatures, and (iii) altered climate variability and seasonality, including the occurrence of extreme events (*e.g.*, heatwaves, droughts, storms and floods). In addition, human systems and ecosystems are vulnerable to major events associated with climate change such as river floods or coastal flooding. The second volume of the fifth IPCC (Intergovernmental Panel on Climate Change) report presented a synthesis of the current knowledge on the impacts of climate change, on adaptation issues, and on the vulnerability of various sectors, including food production and food safety (IPCC, 2014a). Although some regions may benefit, at least in the short term, from changing climate, most will be negatively affected. In many regions, a combination of different impacts may exacerbate vulnerabilities (*e.g.*, southern and south-eastern regions of the EU). Therefore, adaptation of agriculture to climate change is a key challenge for the future of human societies, especially for perennial crops like grapevine. This paper is based on the concluding presentation of the ClimWine 2016 Symposium (Bordeaux, 10-13 April 2016).

Agriculture and climate change

Negative, but also sometimes positive, effects of climate change on crop and terrestrial food production are already evident in several regions of the world. Climate change is partly responsible for yield stagnation or decrease for major crops such as wheat, soybean or maize (see *e.g.*, Brisson *et al.*, 2010; Bassu *et al.*, 2014; Asseng *et al.*, 2015; Mourtzinis *et al.*, 2015). The overall relationship between climate change and yields is often crop and region specific (Rosenzweig and Parry, 1994; McGrath and Lobell, 2013), depending for example on differences in baseline climate, management and soil, and the duration and timing of crop exposure to climate stress. Although some uncertainty remains, projected impacts on mean crop yield are increasingly pessimistic as the end of the 21st century is getting closer, with low latitude regions being subject to more severe climate change impacts (Rosenzweig *et al.*, 2014). Increased interannual yield variability has already been observed in some regions and it is forecasted to increase (IPCC, 2014a; Iizumi and Ramankutty, 2016). Implementing adaptation strategies may partially balance the negative impacts of climate change but their effectiveness appears to be highly variable according to the crop and region under consideration. It is therefore necessary to mobilise research, innovation and transfer capacity in many areas to improve adaptation strategies.

Regarding viticulture, global warming will affect grapevine (especially its phenology, as shown for example by the PERPHECLIM project; Destrac Irvine *et al.*, 2015) and wine production (Mozell and Thach, 2014). Impacts not only concern grapevine physiology and biochemistry, but also the production methods used to make wine (Mira de Orduña, 2010; Schultz, 2010). This strongly suggests to consider a wide range of adaptation and mitigation methods (see *e.g.*, Battaglini *et al.*, 2009; Bernetti *et al.*, 2012; Lereboullet *et al.*, 2013).

Mitigation and adaptation as complementary strategies

The possible response of human societies to the impacts of climate change is often presented according to two potential strategies, mitigation and adaptation. Mitigation involves reducing the magnitude of climate change through emissions reductions (IPCC, 2014b) and geoengineering (Shepherd, 2009; UNESCO, 2011), somehow offsetting the effects of greenhouse gas emissions (yet there is growing awareness of the potential for serious negative impacts of geoengineering; UNESCO, 2011). A number of mitigation strategies in the agriculture sector have been identified as useful in stabilizing atmospheric concentrations of greenhouse gases, including reduction of non-CO_2 gases (*e.g.*, CH_4, N_2O), such as improved crop and livestock management and agroforestry practices, enhanced soil carbon sequestration in agricultural soils, improved nitrogen fertilizer application techniques to reduce N_2O emissions or improved energy efficiency (Tubiello, 2012).

Climate change adaptation focuses on preparing for, coping with, and responding to the impacts of current and future climate change (Stein *et al.*, 2013). According to IPCC, adaptation may be defined as "*the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects*." (IPCC, 2014a). Overall, adaptation should prioritize flexible and "non-regret" options with long-term perspective (Hallegatte, 2009). Adaptation to climate change focuses primarily on active or passive human responses. It should be distinguished from adaptation in the evolutionary biology sense, which focuses on genetic changes over time in response to selective pressures (Stein *et al.*, 2013). Evolutionary adaptation plays an important role in adaptation to climate change through, for example, the capacity of species and populations to naturally adjust to changing conditions through genotypic shifts or phenotypic plasticity (Hoffmann and Sgrò, 2011).

Various types of adaptation strategies may be identified depending on the magnitude of changes they imply (Figure 1). Incremental adaptation can be defined as the extension of actions and behaviours that already exist in order to avoid the disruption of a system (Berrang-Ford *et al.*, 2011; Kates *et al.*, 2012). However, adaptation to more extreme scenarios can no more be an extrapolation of practices suitable for less-dramatic cases, and it may be necessary to criticize or challenge current systems and paradigms (Pelling, 2011). According to Smith *et al.* (2011), adaptation needs to be reconceptualised and designed as a continuous and transformative process, rather than intermittent and incremental. Under future climate, risk or vulnerability may be high, making drastic adaptation necessary, what is then called transformational adaptation (Kates *et al.*, 2012; Rickards and Howden, 2012). According to Rickards and Howden (2012), transformational adaptation can be *fitting to* or *fitting with* the environment, depending how it is intellectually framed. The first conception sees nature as something external, in which we live, and tries to avoid negative outcomes due to increased risk and vulnerability (Kates *et al.*, 2012; Rickards and Howden, 2012). The second one emphasises understanding the roots of vulnerability, and sees society as an agent of change rather than a mere spectator, thus trying to co-evolve with the socio-ecological system (Pelling, 2011; Rickards and Howden, 2012). Transformational change may imply shifts in locations for production of specific crops and livestock, or shifting to farming systems new to a region or resource system. Systemic adaptation occupies an intermediate situation between incremental and transformational adaptation.

Many adaptation and mitigation options can help address climate change, but no single option is sufficient by itself (IPCC, 2014c). Although highly significant research efforts have been made in the last decade, both mitigation and adaptation options still raise many questions for research (see *e.g.*, Tubiello, 2012; UNEP, 2013). Effective adaptation and mitigation responses will depend on policies and measures across multiple scales: international, regional, national and sub-national (IPCC, 2014a, 2014b). Their effective implementation requires integrated responses that link adaptation and mitigation with other societal objectives, prompting for organisational and institutional changes (Berkhout *et al.*, 2006; RCEP, 2010). Education, training, capacity-building and the development of human and social capital are other key success factors (Anderson, 2012; Castle *et al.*, 2015; Mochizuki and Bryan, 2015).

The INRA metaprogramme on Adaptation of Agriculture and Forests to Climate Change (AAFCC)

1. AAFCC background and objectives

Considering the research needs prompted not only by climate change but also by other challenges, the French National Institute for Agricultural Research (INRA) has launched in 2010 a series of

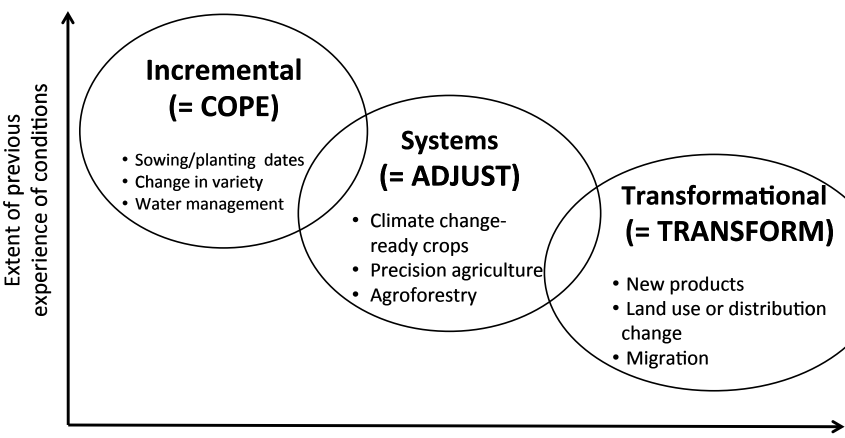

Figure 1. Levels of adaptation in relation to the extent of previous experience of climate conditions and to the degree of climate change (modified from Thornton 2014).

multidisciplinary research programmes, the metaprogrammes. These metaprogrammes aim at structuring and coordinating research activities and projects on key challenges.

The metaprogramme on Adaptation of Agriculture and Forests to Climate Change (AAFCC) was launched in 2011. It intends to play a role in the coordination, promotion and integration of the activities in agricultural research to overcome the scientific and societal barriers that could restrict adaptation. This strategy involves cooperation with French and foreign academic and socio-professional actors. It should ensure rapid results and progress, for example in multi-criteria assessment of adaptation options. It also intends to strengthen the outreach of French agricultural research. The metaprogramme is also a way to implement the scientific priorities identified by INRA and its partners of the thematic group "Climate: change, adaptation, mitigation, and impacts" of the national alliance for environment (Allenvi). Favouring dialogue between disciplines, AAFCC therefore provides a framework for the various research projects on adaptation of agriculture and forests to climate change.

Several objectives have been assigned to AAFCC (Figure 2):

- assessing and managing the mid-term risks and opportunities, and defining strategies aimed at anticipating and mitigating climate crises;

- planning and developing scenarios (including quantitative estimates of uncertainty) for the regional impacts of climate change on agriculture and managed ecosystems (permanent grasslands, forests);

- understanding and controlling the main effects of climate change on biodiversity and its evolution, as well as the health of ecosystems, agro-systems and livestock;

- genetically improving cultivated, domesticated and livestock species, and strengthening the resilience of the different sectors as well as the crops and production systems;

- developing innovative adaptation technologies compatible with reducing emissions and increasing or maintaining the size of greenhouse gas sinks;

- identifying the costs and benefits of adaptation measures in respect of the various issues at stake (economic performances, biodiversity, water and soil resources, food supply, quality and safety); and

- establishing collective organisation systems (governance, insurances, training, innovation, valorisation) that can strengthen the resilience of agriculture and forestry to climate change.

2. Multidisciplinarity and integration as keywords

Discipline-related skills in human and social sciences (*e.g.*, economy, politics, sociology, etc.), life sciences (*e.g.*, agronomy, ecology, genetics, ecophysiology, animal sciences, etc.), Earth and planetary sciences (*e.g.*, hydrology, climatology, Earth observation, etc.), or mathematics and informatics (*e.g.*, modelling, statistics, "Big Data", etc.) should be mobilised to cover the range of questions raised by adaptation to climate change. The chosen strategy focuses on integrated approaches at the sector or territorial level. There is a strong need for

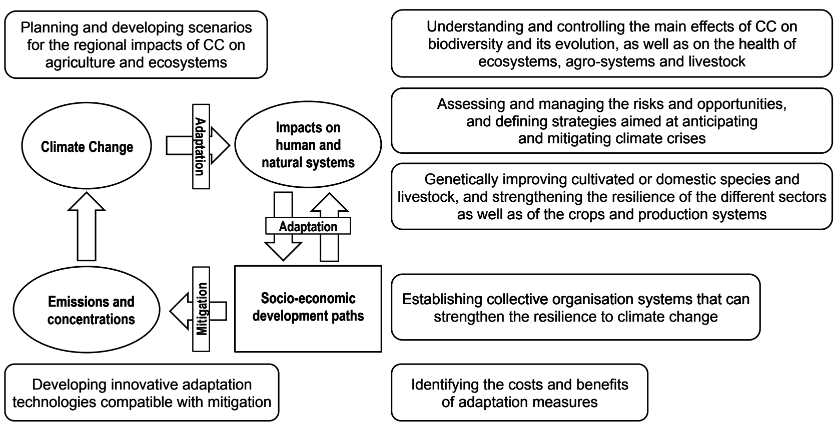

Figure 2. Main objectives of the INRA metaprogramme on Adaptation of Agriculture and Forests to Climate Change (AAFCC), with their position relative to the human societies-climate system.

cooperation between multiple disciplines and for co-construction of research projects.

Elaborating and supporting the process of adapting food systems to climate change is a major issue. Due to its multidisciplinary nature, the approach requires promoting interactions between scientists, development actors and stakeholders of the concerned sector. Building a common vision of possible futures and key issues is a vital initial step in the development of prospective scenarios for adaptation. As in other fields, involving the actors in the research projects (*e.g.*, citizen science, participatory action research, participatory breeding, participatory integrated assessment; German *et al.* 2012; Entz *et al.* 2015; Huang *et al.* 2015) may contribute to the definition and implementation of innovative solutions.

Multidisciplinarity is strongly promoted by AAFCC, for example in the case of viticulture through the LACCAVE project (Ollat and Touzard, 2014): What are the biotechnical leverage actions for maintaining grape production, both in quantity and quality, under future climate? What are the risks and solutions regarding the increase of climatic hazards? Can winemaking process adapt to face the increase in grape sugar content? Will consumers' tastes and preferences change? How to deal with these changes? Answering to these questions that cascade down from producers to consumers requires the implementation of multi-criteria analysis and forward-looking approaches.

Modelling of climate change impacts on agriculture is also a key issue of current research activities. Using a set of different models for estimating the uncertainty around a projection (also known as ensemble modelling) is a common practice in climatology, for example in IPCC work. Its use in agronomy is far more recent. International programmes on crop or grassland modelling such as AgMIP (*The Agricultural Model Intercomparison and Improvement Project*; Rosenzweig *et al.*, 2013) and MACSUR (*Modelling European Agriculture with Climate Change for Food Security*; Bindi *et al.*, 2015) are currently under way. French modellers granted by AAFCC actively contribute to yield modelling for grasslands, maize or wheat. The use of multiple models enhances the reliability of the simulation of the impacts of future climate scenarios. These programmes also support the comparison and improvement of ecophysiological models. They contribute to strengthen the links between modellers at the international level and to initiate new projects.

3. Multiple dimensions of work

Since 2011, AAFCC has supported more than 30 research projects and international actions and networks. Research projects address annual and perennial crops, livestock, forest, biodiversity or water and soil resources. AAFCC has also promoted the training of young scientists through PhD grants and postdoctoral fellowships. Indeed, capacity-building through both initial and continuous training and education should also be a key component of any initiative on adaptation to climate change.

The issues and general objectives of the programme can globally be ordered according to the response time of the systems, from short- to long-term, and the intensity and 'active' nature of the adaptation, from palliative or support actions to innovation and technical or collective organisational breakthroughs. Such breakthroughs require strong innovations and a thorough socio-economic assessment.

The actions supported by AAFCC also include observations and experiments on agro-systems, ecosystems and socio-systems, and modelling for integrating knowledge and elaborating scenarios for future climate and practices. In addition, support to transfer and analysis of current strategies as well as multi-criteria assessment are implemented to elaborate innovations that should be efficient, economically realistic and socially acceptable.

4. Supporting the development of tools for adaptation and climate services

Adaptation to weather events has always been a challenge for human societies, prompting for innovation in many sectors of human activities, especially agriculture. To some extent, it should therefore be possible to adapt to future climate conditions by modifying or extending existing technologies, sometimes dating back hundreds of years. People may adapt to climate change simply by changing their behaviour or by changing their occupation. They may also employ different forms of technology, whether "hard" forms, such as new irrigation systems or drought-resistant seeds, or "soft" forms, such as insurance schemes or crop rotation patterns. Combinations of hard and soft solutions may also be implemented, as with early warning systems that combine hard measuring devices with soft knowledge and skills that can raise awareness and stimulate appropriate action.

Table 1 presents some examples of innovation domains for different sectors that may be of interest for the adaptation of agriculture to climate change. Some of the corresponding technologies are already available and widely used. Others need to be further developed or adapted. The AAFCC metaprogramme intends to play a role in this perspective. Climate change has caused the outbreak of a set of new services, entitled "climate services", for which AAFCC should play a key role. In the context of the European Commission's climate services initiative, the term "climate services" has a broad meaning (European Commission 2016): "*Transforming climate-related data and other information into customised products such as projections, trends, economic analysis, advice on best practices, development and evaluation of solutions, and any other climate-related service liable to benefit that may be of use for the society. These services include data, information and knowledge that support adaptation, mitigation and disaster risk management*".

The climate services market already represents a business activity with specialized actors (consultants, foundations, insurance companies) and many emerging services, especially regarding scenario making and impact assessment. AAFCC aims at increasing the range of available services through the proposal of a service portfolio at the national scale with different temporal perspectives according to the considered sectors. This portfolio will rely on tools, maps and graphic illustrations elaborated using an agro-hydro-climatic modelling chain. Models should provide quantitative estimates of the impacts of climate and practice changes on fluxes and yields. They should also provide indicators useful for the assessment of the efficiency of adaptation measures. Using a modelling chain, it will be possible to visualize different elements, from climate to water resources, integrating agricultural or forestry activities and the influence of climate, irrigation and aquifer level. Decision-making tools will be produced for integrated and shared management of water resources as well as for adaptation of agriculture and forests to climate change, to support adaptive management and strategic adaptation at different scales.

5. Fostering international cooperation

Tackling the questions related to adaptation of agriculture to climate change requires strengthening the international cooperation between research organisations. AAFCC is in line with the European Joint Programming Initiative on "Agriculture, food security and climate change" (JPI FACCE), which aims at enhancing coordination of national research programmes. In addition to the coordination and rationalization of research efforts between member states, working at a supra-national scale is relevant for encompassing a diversity of climatic and soil conditions and increasing the generic nature of the findings. International partnerships also provide interesting support to prediction. Their reinforcement is also necessary to fully take advantage of the various environmental observatories distributed across Europe and worldwide. AAFCC supports various European initiatives through funding of ERA-NETs (*e.g.*, ERA4CS, Foresterra). It also supports international projects (*e.g.*, cooperative projects with India or south Mediterranean countries) and global initiatives (*e.g.*, ensemble crop modelling in AgMIP and MACSUR). Considering the issues at stake, international cooperation is undoubtedly, along with multidisciplinarity, a key issue in this domain.

6. Fostering dialogue with stakeholders

A Stakeholders Committee (SC) of the AAFCC metaprogramme was set up. It is intended to serve as the preferential contact point with the representatives from the different concerned communities (ministry and state agencies, technical institutes, forest managers, representatives from agricultural sectors, competitiveness clusters, NGOs, etc.). It gives advice on the adequacy between on-going activities and

Table 1. Examples of innovation domains for various sectors useful for the adaptation of agriculture to climate change.

Sector	Examples of innovation domains
Water management	Purification, desalination, irrigation, water reclamation and reuse
Agricultural technologies	Sensors, UAV, embedded softwares, machinery
Information and communication technologies	Weather forecast, climate monitoring, GSM diffusion
Infrastructures	Civil engineering, livestock buildings
Agri-food industry	Conservation, processing of agricultural products
Agricultural consulting	Decision-support tools, climate services

needs, and on the impact of metaprogramme activities for stakeholders. It supports the development of AAFCC activities and contributes to their improvement through the co-construction of proposals and priorities for future actions. It also advises on the elaboration and implementation of the strategic agenda of AAFCC, especially from the training and transfer perspectives. Associating stakeholders to research activities is a key element for the success of such a programme (Conde and Lonsdale, 2005; Rotter *et al.*, 2013).

Conclusion – Food for thought from the ClimWine 2016 Symposium

ClimWine 2016 successfully gathered a highly diverse community of scientists from various countries and disciplines, demonstrating that addressing the numerous challenges associated with climate change for grape and wine production is clearly a multidisciplinary task. The following items summarize some key aspects that were addressed during this conference. They are described in much more details in various papers in this issue.

- The event was entitled "*Sustainable grape and wine production in the context of climate change*". The presentations clearly showed that although intensive research activities have been performed for several years, especially during the LACCAVE project, this is still a highly challenging question, not only for research but also for all the actors, including consumers.

- Opportunities associated with climate change should not be forgotten, at least for the medium term, but it is necessary to avoid over-optimism, since long-term perspectives are a concern in many areas of the world, especially if the worst scenarios should emerge.

- Most studies are still dealing with impacts of climate change. There is an urgent need for moving from impact to true adaptation studies, *i.e.*, considering all the dimensions of the question, including social and economic aspects.

- Diversity of situations in terms of environmental conditions (climate, soil, etc.), practices, social systems and production objectives strongly support the need for customized solutions. These solutions should combine operational (*i.e.*, reactive) and strategic (*i.e.*, anticipatory) options.

- Whatever the situation, there is a need for holistic approaches that include grape, water, soil, pests, etc. This is not only a matter of biotechnical sciences and mathematical models (although they are essential), and there is clearly a need for an integrated response across the value chain and including actors (*e.g.*, participatory research).

- Communication to the general public and involvement of all stakeholders are key elements of the strategy. The associated costs for scientists in terms of time or media pressure may be very high but the results are worth it.

- Finally, capacity-building and initial and continuous training and education are among the main keys to the future success of sustainable grape and wine production.

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Viticulture in Portugal:
A review of recent trends and climate change projections

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Abstract

Aim: The winemaking sector in Portugal is of major socio-economic relevance, significantly contributing to the national exports and sustaining many wine-related activities, including oenotourism. Portuguese viticultural regions present a wide range of edaphoclimatic conditions with remarkable regional specificities, thus contributing to the individuality of their wines. Owing to the strong influence of climate and weather factors on grapevines, climate change may drive significant impacts on Portuguese viticulture.

Methods and results: Climatic projections for the next decades in Portugal highlight an overall warming and drying trend of the grapevine growing season, potentially resulting in modifications in phenology, growth, development, yields and eventually wine characteristics and typicity. Furthermore, the current viticultural suitability of each region is projected to undergo significant changes, suggesting a reshaping of the optimal conditions for viticulture throughout the country. In order to sustain high quality levels and affordable yield regularity, cost-effective, appropriate and timely adaptation measures must be implemented by the sector.

Conclusion: The most recent scientific studies covering the potential impacts of climate change on Portuguese viticulture are herein presented.

Significance and impact of the study: Possible adaptation measures against these threats are also discussed, foreseeing their integration into decision support systems by stakeholders and decision-makers.

Keywords: *Vitis vinifera*, viticulture, wine regions, Portugal, climate change

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Viticulture and winemaking in Portugal

1. Socio-economic context

In Portugal, winemaking is historically one of the most relevant socio-economic activities. In the context of the overall agricultural sector (e.g. cereals, vegetables), this industry represents roughly 14% of the total planted area and 6% of the total productions (INE, 2016). With an average vineyard area of over 200 thousand hectares and a yearly wine production of about 6 million hectolitres (IVV, 2013), the national production has shown a slight decrease over the past decade (-2%/yr), which can be mostly attributed to the gradual decrease in vineyard area (-1%/yr). Nonetheless, Portugal is currently the 11th wine producer and the 10th exporter in the world (OIV, 2013), which is a remarkable outcome taking into account the size of the country. Approximately half of the total annual wine production is currently being exported. In absolute terms, this contributes to the national exports with over 700 million €/yr, which corresponds to nearly 2% of total national exports. A major factor for this success is the wide recognition of Portuguese wines in foreign markets, just to mention the renowned Port wine.

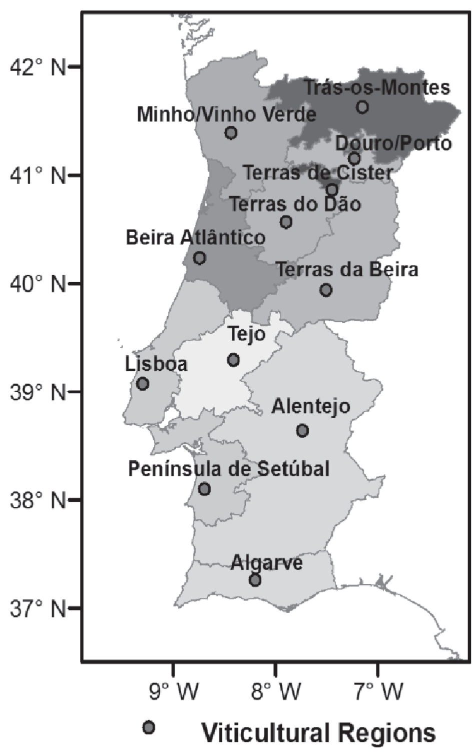

Figure 1. Wine regions in mainland Portugal. The Azores and Madeira archipelagos are not shown.

2. The winemaking regions

Portugal comprises a total of 14 wine regions (mainland Portugal, Azores and Madeira archipelagos) (Figure 1), which include 31 Protected Denominations of Origin. In the north, the Douro Demarcated Region, with almost 1.5 Mhl of total wine production and 45,000 ha of vineyards, is the oldest and one of the most important wine regions of the country. This region, famous for its Port wine, is responsible for one fourth of all wine produced in Portugal (IVV, 2013), and its vineyard landscape is also considered World Heritage by the UNESCO since 2001. In the northwest, the most maritime area of Portugal, the Minho wine region produces mostly white wines, distinguishable for their typical freshness and slightly higher acidity. In the south, the Alentejo wine region, with typical Mediterranean climates, has undergone remarkable growth rates over the recent decades and is currently the leading region in terms of non-fortified wine production. In general, from the sparkling wines of the Beira-Atlântico region to the fortified Madeira wine, many other regions in Portugal present unique wines resulting from their specific *terroirs*. The wines of Portugal are thereby valuable national brands, increasingly recognised worldwide.

3. The climate and the soils

Overall, the wine regions in mainland Portugal present Mediterranean-like climatic conditions, with warm dry summers and mild wet autumns-winters. In the northern/coastal areas (i.e. Minho and Beira-Atlântico), the Atlantic influence is strong, resulting in relatively high precipitation totals (>1,000 mm). In general, temperatures are higher in the south (e.g. Alentejo) and lower in the north (e.g. Minho and Trás-os-Montes). In the inner areas, however, summertime low water availability critically limits grapevine development (inner Alentejo and Douro). Winter temperatures tend to be milder in the southern regions, such as in Lisboa and Algarve (January mean temperature of 10–12ºC), though late spring frost is common in some northern regions (e.g. Terras do Dão), which may lead to important damages in vineyards.

Growing degree-day (GDD (Winkler, 1974); April–October, 1950–2000) climatologies over Portugal (Figure 2a) indicate that the northern regions typically show temperate climates, with cool areas at higher elevations and warm/temperate-warm areas at lower elevations, especially in the Douro region. Almost all of the southern part of the country shows a warm climate, but with some inner areas already in the very-warm class. Regarding dryness conditions (Dryness Index (Tonietto and Carbonneau, 2004); April–September, 1950–2000), the Atlantic influence is noticeable in the northern coastal areas, with sub-humid or even humid climates (Figure 2b), whereas the rest of the country depicts moderate dryness.

There are two main soil types in Portugal: cambisols in the centre-north and lithosols/luvisols in the south (FAO, 2006). The most important exceptions are the Douro region in the north, with lithosols, and the Peninsula-de-Setubal and Tejo regions, with podsols. Loam is the predominant soil texture in Portugal, while sand and clay are less frequent (Fraga *et al.*, 2014a). With respect to physiography, the most mountainous areas are located in inner northern and central areas, northwards of the Tagus River, while flatlands prevail in coastal and southern areas.

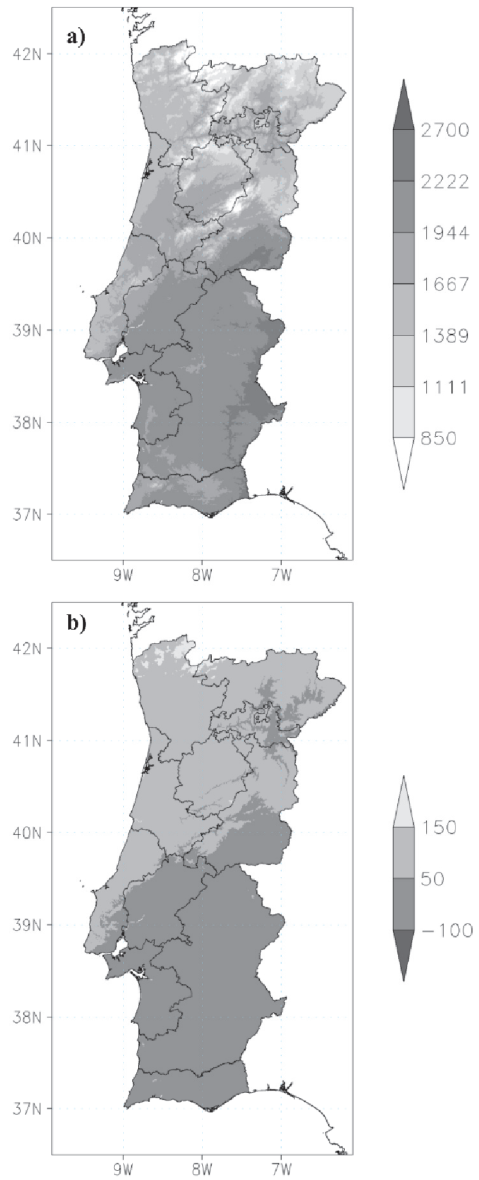

Figure 2. a) Growing degree-days and b) Dryness Index calculated for the growing season (April–September, 1950-2000) over Portugal.

4. The varieties and practices

Portuguese vineyards preserve a large number of autochthonous and international varieties, with over 300 authorized varieties. Aragonez or Tinta-Roriz (also known as Tempranillo, red) is the most planted variety in Portugal, followed by Touriga-Franca (red), Castelão (red), Fernão-Pires (white) and Touriga-Nacional (red). These varieties are present in nearly all regions. Other varieties are more region-specific, such as Alvarinho (white) in Minho or Baga (red) in Beira-Atlântico. All these varieties present unique agronomic and oenological characteristics that ultimately result in distinctive wines, either mono-varietal or blended, though blended wines are more traditional, including the Port wine. The cordon (unilateral or bilateral) is the most used training system, though pergola (in Minho) and gobelet (e.g. Trás-os-Montes) can also be found. Phenological timings (budburst, flowering, veraison and maturation), although varietal-dependent, tend to occur earlier in the southern/warmest part of the country. Budburst occurs from March to April and flowering in May–June, while harvest is typically carried out from late August to early October.

Climate change

1. Climate change projections

Atmospheric conditions are one of the most important controlling factors for the growth and productivity of grapevines (Keller, 2010). In fact, grapevine physiology and berry composition are highly influenced by air temperatures during the growth cycle (Keller, 2010). Furthermore, winter chilling is also very important for bud dormancy (Bates *et al.*, 2002; Field *et al.*, 2009). Consequently, a base temperature of ca. 10ºC is required to break this dormancy period and to onset the growing/vegetative cycle (Amerine and Winkler, 1944; Winkler, 1974). Despite its high adaptability to different climatic conditions and its resilience to moderate water and heat stresses, this crop can be severely affected by stresses derived from extreme weather events. Extremely low negative temperatures in spring may significantly damage grapevine development (Branas, 1974). Grapevines are also very sensitive to frost and hail during their vegetative period (e.g. Spellman, 1999). Heat weaves may also considerably affect physiology and yields (Kliewer, 1977; Mullins *et al.*, 1992).

According to the International Panel on Climate Change, global temperature is expected to rise from 2 to 5ºC by 2100 (IPCC, 2013). For Portugal, temperature projections are in agreement with these changes, while precipitation is expected to decrease, particularly in the south-innermost areas (SIAM2, 2006). The recent climatic trends over Portugal are already in line with these climate projections (Fraga *et al.*, 2012).

For the future, an overall warming and drying of the grapevine growing season is indeed anticipated (Fraga *et al.*, 2012; Fraga *et al.*, 2014b). GDD projections for 2041-2070 under the IPCC A1B scenario suggest large increases in accumulated temperatures (Figure 3a), particularly in the innermost regions, reaching values above 2700 ºC (excessively hot class). In addition to the overall warming, the drying trend will lead to changes in the DI patterns. Severe dryness is likely to occur in the future, particularly in the innermost southern regions (Figure 3b). The expected decrease in rainfall in spring and summer will enhance water requirements and may trigger severe water stress in vineyards. Moreover, updated projections following the IPCC RCP scenarios are in close agreement with these outcomes (Fraga *et al.*, 2016a). Given the key role played by atmospheric factors on viticulture, climate change is expected to bring new challenges to this crop.

2. Impacts on phenology

Grapevines will be particularly affected by the projected higher temperatures during the growing season. As temperatures are a major driver of the grapevine development stages (Parker *et al.*, 2013), significant warmings are expected to lead to earlier onsets (Bock *et al.*, 2011; Chuine *et al.*, 2004; Dalla Marta *et al.*, 2010; Daux *et al.*, 2011; Jones *et al.*, 2005a; Molitor *et al.*, 2014; Sadras and Petrie, 2011; Webb *et al.*, 2011). Recent studies for Portugal isolated future projections for the phenological stages of 16 native varieties under RCP4.5 and 8.5 (Fraga *et al.*, 2015; Fraga *et al.*, 2016c; Malheiro *et al.*, 2013). The results hint at earlier onsets of 2–5 days for budburst and flowering, and of 7–15 days for veraison until 2070, depending on the selected future scenario and variety.

Earlier phenological timings will bring heterogeneous outcomes. Earlier budburst and flowering may result in substantial increases in the risks of frost damages. Given the projected increase of grapevine-related pests/diseases (Francesca *et al.*, 2006; Valero *et al.*, 2003; Van Niekerk *et al.*, 2011), this may also entail increased risks and cause a strong impact on management practices. Extreme heat during this period may abruptly reduce vine metabolism, affecting the aroma and colour of wines. Still, higher sugar concentrations and lower acidity are expected, which may potentially increase the risk of organoleptic degradation or even spoilage (Orduna, 2010), threatening the production of well-balanced wines.

3. Impacts on yield

Under future climates, the potential impacts on grapevine yield can be very diverse. The interaction between negative (higher heat and water stresses) and positive (enhanced CO_2 effect on plant physiology) climate change effects on yields are expected to lead to different outcomes (Bindi *et al.*, 1996; Fraga *et al.*, 2014c). Basically, the overall effect on production will depend on CO_2 concentrations, temperature, solar radiation, precipitation and many other factors. As an example, for the Douro region, several studies suggest higher grapevine yields and wine productions in future climates (Gouveia *et al.*, 2011; Santos *et al.*, 2011; Santos *et al.*, 2013). Nonetheless, these studies were conducted considering the more humid part of the region (Baixo-Corgo), while projections for the driest areas hint at yield decreases (Cima-Corgo and Douro-Superior). Furthermore, yield decreases are also projected to occur in the Alentejo region (Coelho *et al.*, 2013), which shows a much warmer and drier climate. Although projections for yield are largely heterogeneous and site-specific, most studies agree regarding the projections for the annual yield irregularity. The expected increase in the frequency and intensity of weather extremes (Andrade *et al.*, 2014) will lead to higher inter-annual yield variability, which may affect the whole winemaking sector (Jones *et al.*, 2005a; Schultz, 2000).

4. Impacts on wine quality

Under future warmer climates, extremely high temperatures may inhibit the formation of anthocyanins (Buttrose *et al.*, 1971), impacting berry colour and aroma (Bureau *et al.*, 2000; Downey *et al.*, 2006). Higher sugar concentrations and lower acidity are also expected under future warming. For regions already presenting warm climates (e.g. Alentejo, Douro), climate change may thus endanger the balanced ripening of grapes and the sustainability of the existing varieties and wine styles (Fraga *et al.*, 2016b; Jones and Alves, 2012). However, future warming in the cooler climate regions (e.g. Minho, Beira-Atlântico) may improve suitability for the production of high quality wines. As such, although a modification of the currently established wine types may occur, the socio-economic impacts of climate change on wine quality can be quite diverse.

Adaptation measures

As a protection strategy against the unwanted impacts of climate change, adaptation measures should be considered, focusing on specific problems. Adequate and timely planning of these measures needs to be adopted by the winemaking sector. The readiness to define and implement adaptation strategies to climate change will result in lower detrimental impacts to the sector (Barbeau *et al.*, 2014; Battaglini *et al.*, 2009; Olesen *et al.*, 2011). These strategies may include short-term measures, such as changes in viticultural management practices, grown varieties or even oenological practices (Neethling *et al.*, 2016). Additionally, long-term adaptation measures should also be considered, as some regions may become excessively warm and dry. These different types of adaptation measures are discussed in the following subsections.

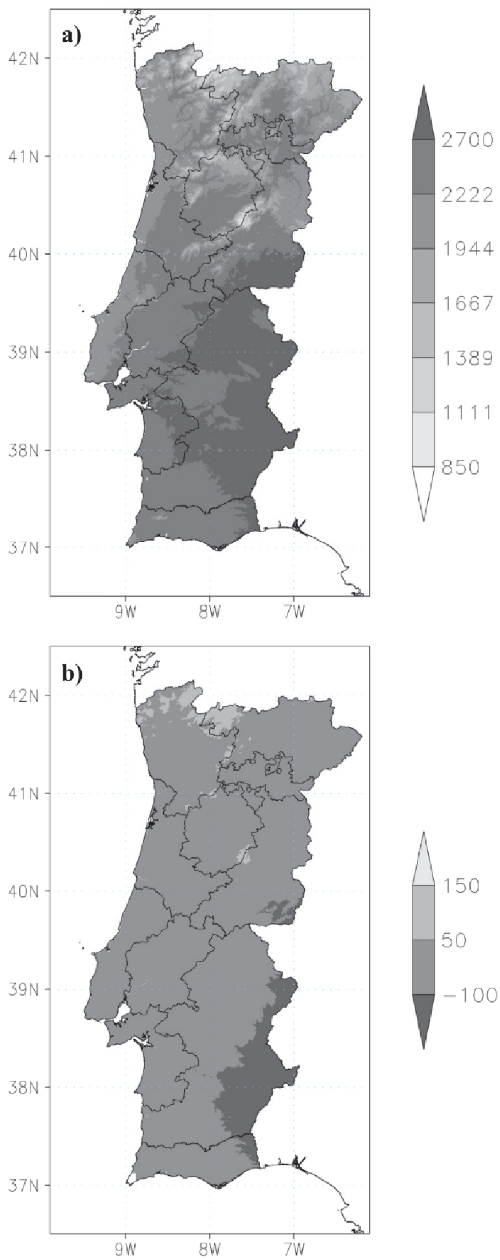

Figure 3. a) Growing degree-days and b) Dryness Index calculated for the growing season (April–September) over Portugal for 2041-2070 and the A1B scenario.

1. Short-term adaptation measures

Taking into account the warming trend projected for the future, selecting varieties with higher thermal requirements and higher stress resistance may strengthen the overall resilience of the Portuguese viticulture under future climates (Fraga *et al.*, 2016b). Therefore, preserving the existing biodiversity is critical, as some varieties may thrive in the future and may thereby be part of the solution. Furthermore, oenological practices may also play a key role in maintaining regional wine typicity and quality.

Regions under severe dryness, such as Alentejo and Douro, should promote higher water use efficiencies (Flexas *et al.*, 2010) by adopting training systems that promote shorter trunks and lower total leaf areas, such as gobelet. The selection of more drought tolerant rootstocks must also be regarded as a possible adaptation measure (Harbertson and Keller, 2012; Keller *et al.*, 2011). Changes in tillage systems and soil management should also be considered (Bahar and Yasasin, 2010; Kvaternjak *et al.*, 2008). One of the most controversial (in Portugal) measures is the application of water by irrigation, but smart irrigation strategies can promote a balanced compromise solution between environment, economy and plant water requirements (Chaves *et al.*, 2007; Chaves *et al.*, 2010; dos Santos *et al.*, 2003; Ferreira *et al.*, 2012).

Excessive solar radiation can also be damaging for grapevines, already under water and heat stresses. Shading materials, either natural (e.g. olive trees) or artificial, can help overcome this shortcoming (Greer *et al.*, 2011; Shahak *et al.*, 2008). Furthermore, the use of chemical sunscreens for leaf protection against sunburns may also represent an important alternative (Dinis *et al.*, 2016). Another option to consider is the adjustment of the implemented training system (Pieri and Gaudillere, 2003). Changing canopy geometry or orientation can also significantly influence light interception (Grifoni *et al.*, 2008; Intrieri *et al.*, 1998).

2. Long-term adaptation measures

Long-term adaptation measures should also be considered, although their extent and application may bring significant socio-economic implications. These measures include changing vineyard location, as some regions may become excessively warm and dry (Fraga *et al.*, 2016b; Moriondo *et al.*, 2013). Relocations of vineyards to cooler sites, such as higher elevations, coastal zones or simply areas with lower solar exposures, are possible measures.

Conclusions

Although climate change is expected to drive significant changes on Portuguese viticulture, large uncertainties still remain regarding the true extent of its impacts. The expected warming and drying trends throughout Portugal may bring some additional challenges for grapevine production (Santos *et al.*, 2011). Increases in the growing-season mean temperatures are indeed expected not only in all of the Portuguese winemaking regions, but also in other regions worldwide (Duchene and Schneider, 2005; Jones *et al.*, 2005b; Neumann and Matzarakis, 2011). This will lead to earlier phenological timings, with potential detrimental impacts (Bock *et al.*, 2011; Chuine *et al.*, 2004; Dalla Marta *et al.*, 2010; Webb *et al.*, 2008). Some southern regions are projected to become excessively dry to grapevine production using the currently established viticultural practices and varieties. Additionally, enhanced risks of pests and diseases in vineyards can be an additional threat (Francesca *et al.*, 2006; Valero *et al.*, 2003; Van Niekerk *et al.*, 2011).

The implementation of adaptation measures is urging, as scientific confidence for significant climate change in the upcoming decades is growing. Appropriate measures need to be addressed by the wine industry to face climate change impacts, mainly by developing suitable strategies at regional scales (Metzger *et al.*, 2008). Winegrape growers are becoming progressively more aware of this problem (Battaglini *et al.*, 2009), since timely strategic planning will provide competitive advantages. Nevertheless, in order to effectively cope with the projected changes, continuous research is needed as climate change is progressing. As such, it is up to the decision-makers and stakeholders from the winemaking sector to implement actions against climate change. These actions will critically contribute to the future economic and environmental sustainability of the Portuguese viticulture.

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Adapting the wine industry in china to climate change: challenges and opportunities

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Abstract

Recently, China has become an exciting wine consumer market and one of the most important wine producers. China's domestic wine industry is in the enviable position of contributing approximately 70 % of the total wine consumed with a 1.36 billion population market and the second largest world economy. Current studies of the Chinese wine industry are mostly focused on the wine market. However, global climate change, which affects the quantity, quality and distribution of wine, will have a strong impact on the Chinese domestic wine industry. In this paper, we characterize the impact of climate change in China and establish policy, financial, technical, institutional and collaborative adaptation strategies for the Chinese wine industry.

Key words: climate change, wine industry, China, adaptation strategies

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INTRODUCTION

Global warming is a common challenge for society. The Intergovernmental Panel on Climate Change (IPCC) report presents that increasing mean surface air temperatures over oceans and land have been observed over the last century (IPCC, 2013). Additionally, in several regions of the world it is evident that climate change has affected both terrestrial food production and crop yields (IPCC, 2014). Under climate change, especially in developing countries, such as China, agriculture is the most vulnerable economic sector (Chen S. *et al.*, 2016).

A widespread observation is that climate change will affect both the geographical distribution of the wine industry and the quality of the product. Although wine is not an essential agricultural product for survival, it is closely connected to human history and culture as a significant product of human ingenuity (Mozell and Thach, 2014). Viticulture contributes to the local economy, tourism, industry and natural habitat (Duchene, 2016 ; Resco *et al.*, 2016). In recent years, China has joined the world's wine world presenting significant suitable regions and diverse climatic sites (De Orduña, 2010 ; Hannah *et al.*, 2013). A great expansion of Chinese domestic wineries in new regions with increasing capability may be observed (Mozell and Thach, 2014). While there have been continued improvements in the wine industry, it is necessary to recognize the impact of global climate change, which will bring both challenges and opportunities to China.

In this paper, we review the development of the Chinese wine industry and explore how climate change will affect viticulture and the Chinese wine industry. Next, we provide climate change adaptation strategies for the wine industry in China.

MATERIALS AND METHODS

In this study, we use secondary data collected from the International Organization of Vine and Wine (OIV) and the National Bureau of Statistics of China, the China Sugar and Liquor Yearbook, Chinese business information networks and literature review to examine the development of the wine industry in China.

To better understand how climate change will affect the global wine industry, we explore the structural relationship between climate change and vineyards. We attempt to analyze the possible benefits (opportunities) and harms (challenges) of climate change for the Chinese wine industry based on a number of indicators of both climate variables (temperature, accumulated heat, precipitation, water resource, and frost-free period) and climate events (drought, flood, extreme rainstorm, fog, and hail). For the whole country, secondary data are mainly obtained from three sources : 1. Literature review of studies in China ; 2. Institutes and organizations, such as the China Meteorological Administration, the National Bureau of Statistics of China and the World Bank ; and 3. Government reports and bulletins, such as the Ningxia Statistical Yearbook and the China Flood and Drought Management. For the primary wine-producing provinces, qualitative analyses are made by literature review of Chinese studies.

WINE INDUSTRY IN CHINA

China has a 6,000-year history of grape growing and a 2,000-year history of wine making (Qiu *et al.*, 2013). The Chinese wine history can be traced back to the Han Dynasty when wine was introduced from central Asia. Grapes were planted and wine was produced in the Yellow River region in the northeast (Liu F. and Murphy, 2007). The first Chinese company, Changyu, was established in 1892 in the coastal city of Yantai in Shandong Province (Mitry *et al.*, 2009).

Regionally, China has a large geographical size and distinct topographic situations including grassland areas and semi-arid plateau in the north, oasis and deserts in the northwest, semi-humid basin in the center, forests and plains in the northeast, high-altitude plateau in the southwest and humid coastal areas in the southeast. Vineyards for wine making are widely distributed across the Chinese territory and face a variety of geographical and climatic conditions (Figure 1). The main wine-producing provinces are Xinjiang, Yunnan, Henan, the Central Region including Ningxia, Gansu and Shaanxi, the Bohai Bay Region including Shandong, Hebei and Tianjin, and the Northeast Region including Liaoning, Jilin and Heilongjiang. The Yantai Region of Shandong (1987) and the Ningxia Hui Autonomous Region (2012) are involved with the OIV as observers. Cabernet Sauvignon is the most widely planted wine grape in China with more than 20.000 ha followed by Chardonnay, Cabernet Franc, Syrah, and Pinot (Li H., Li and Yang, 2009).

China's domestic wine production has grown dramatically since the 'reform and opening up' policy in 1978 (Figure 1). According to the OIV, in 2014 China had the eighth largest global wine grape production and the largest global grape production. China has overtaken France as the country with the second largest vineyard area (table grape, wine grape and dried grape) after Spain. In 2015, China had the world's second largest vineyard area (table grape, wine grape and dried grape) and the world's eighth largest wine production (Table 1) (OIV, 2016). Even though the total vineyard area of China is now the second largest in the world, only 10 % are for wine production (Decanterchina, 2016). Hence, further vineyard expansion for wine grape could be expected considering the huge market demand and the vast suitable territory of China.

IMPACT OF CLIMATE CHANGE ON WINE PRODUCTION

The sensitivity of wine production to changing climate factors will pose significant effects on yields and quality, ultimately impacting prices and revenues (Bardaji and Iraizoz, 2015). The decrease in suitable grape planting areas will adversely affect the quantity and quality of wine grapes produced (IPCC, 2014). Figure 2 illustrates the structural relationships between climate change and the wine production process. Vineyard location and climate variables have an immediate impact on grape quality and quantity. The effects of climate variables become apparent during the wine making and the wine storage period. Over the long term, vineyards could be relocated as owners seek more suitable climate conditions in order to maximize grape/wine quantity and quality.

Even though a multitude of individual climate factors have impacts on viticulture, temperature and water supply are the most important factors (Schultz and Jones, 2010).

Temperature plays a key role in viticulture. Each specific grape cultivar has its own range of optimal growing season temperatures, which determine the climate-maturity ripening potential (Table 2) (Jones, 2007). In North China, when the average annual minimum temperature is below -15 °C, it is necessary to adopt the soil-burying method to prevent *Vitis vinifera* from the damage of winter frost, and approximately 90 % of the current vineyards in China need soil-burying (Wang S. *et al.*, 2015). The Soil-Burying Line of China indicating areas with average annual minimum temperature

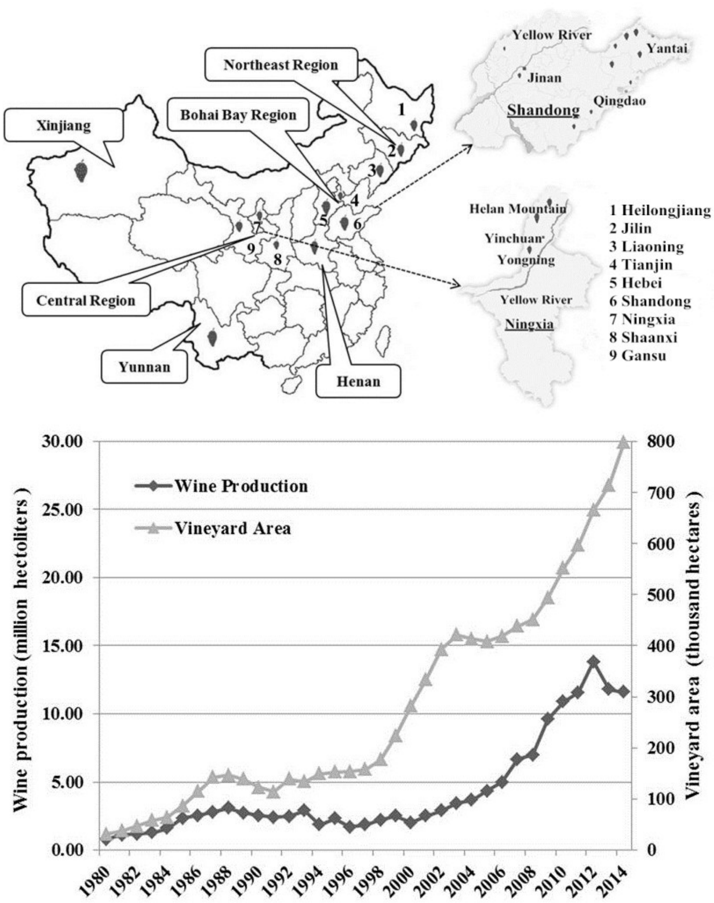

Figure 1. Primary wine-producing provinces and wine production of China. Source: China Sugar and Liquor Yearbook, 2011; Askci, 2015; National Bureau of Statistics of China, 2015.

Table 1. World's grape and wine. Source: OIV, 2016 and calculated by the authors.

Ranking	Country	Wine (2015) million hectoliters	Country	Vineyard (2015) thousand hectares	Country	Wine grape (2014) million tons
1	Italy	50.0	Spain	1,021	France	6.04
2	France	47.4	China	830	Italy	5.87
3	Spain	37.3	France	786	Spain	5.19
4	USA	22.1	Italy	682	USA	3.20
5	Argentina	13.4	Turkey	497	Argentina	2.03
6	Chile	12.9	USA	419	Australia	1.56
7	Australia	11.9	Argentina	225	China	1.48
8	China	11.5	Iran	225	South Africa	1.46
9	South Africa	11.2	Portugal	217	Chile	1.37
Total	World	274.0	World	7,511	World	36.10

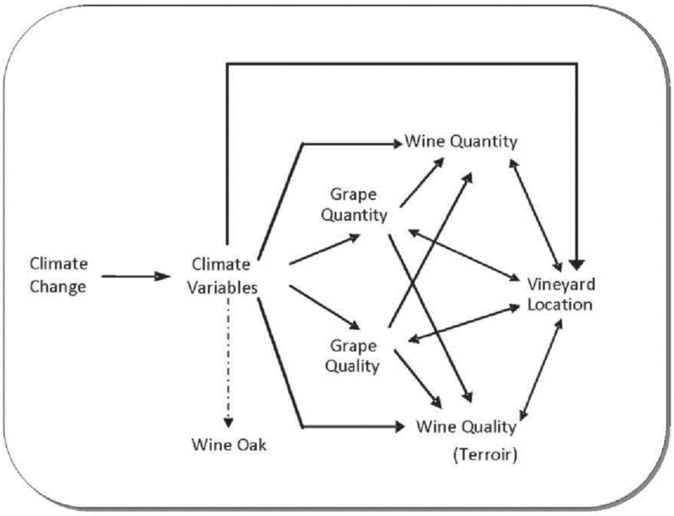

Figure 2. Climate change and the wine production process. Source: Own elaboration.

below -15 °C and requiring soil-burying in winter includes Shandong, Jiangsu, Henan, Shanxi, Shaanxi, Gansu, Sichuan, Yunnan and Tibet from east to west (Li H. *et al.*, 2007b; Li H., Wang *et al.*, 2007). Soil-burying could lead to increased labor intensity and production cost (Zhang J. *et al.*, 2013).

Grapevine growth is initiated by a prolonged temperature above 10 °C in spring (Jones *et al.*, 2005; Holland and Smit, 2014). The sum of mean daily temperature from 1st April to 31st October in the northern hemisphere is an indicator of heat available for wine grape growing defined as the Sum of Average Temperature over the same period (SAT) in viticulture (Jones and Davis, 2000; Szymanowski *et al.*, 2007; Green and Szymanowski, 2012) (Table 2). Another indicator of heat available for viticulture is the Effective Accumulated Temperature (EAT) or the Growing Degree Days (GDD) which is the sum of the temperature value between mean daily temperature and 10 °C from 1st April to 31st October in the northern hemisphere (Amerine and Winkler, 1944; Li H., Li and Yang, 2009; Green and Szymanowski, 2012) (Table 2). Currently in China, accumulated temperatures are mainly used in viticulture climatic zoning studies (Li H. *et al.*, 2007b).

Water availability is a limiting factor for the development of viticulture (De la Fuente *et al.*, 2016). Vine grapes need a suitable amount of water during the growing period. In some cases, excessive rainfall can damage vine roots and grapes and cause floods, while in dry areas additional water supply may be provided by irrigation.

Spring frost will damage the grape buds and affect grape yield and quality; autumn frost will affect carbohydrate synthesis and reduce the cold tolerance ability of grapevine in winter (Li H., Wang *et al.*, 2007). The choice of wine grape planting area is also related to the Frost-Free Period (FFP), which is usually defined as the number of consecutive days between the last day with a temperature below 0 °C in spring and the first day with a temperature below 0 °C in autumn (Wolf and Boyer, 2003; Li H. *et al.*, 2007b). The length of the FFP is often defined by the frost timing in the spring and fall and corresponds to approximately 160-200 days in the vast majority of the world's viticulture regions (Wolf and Boyer, 2003; Jones, 2005). Sufficient FFP is needed in the processes of budburst, flowering, grape ripening, nutrient accumulation and grape frost resistance in winter (Wolf and Boyer, 2003; Li H. *et al.*, 2007b; Holland and Smit, 2014) (Table 2).

In viticulture, we should also consider climate events such as extreme rainstorms, flood, drought, fog and hail which will affect grapevine production. Droughts and extreme rainstorms will have negative impacts on wine grape yield (Castex *et al.*, 2015); hail in summer will damage the shoots, leaves and fruits and affect the yield and quality (Li H. *et al.*, 2007a).

TEMPERATURE AND ANNUAL ACCUMULATED TEMPERATURE

In the past century, China has experienced obvious impacts of global warming in annual mean temperature (10.1°C in 2014) (Figure 3). Data from 156 meteorological stations show that in 2010 the average temperature was 1.23°C higher than in 1950 (Li R.L. and Shu, 2013). The surface temperature in eastern China has increased by 1.52°C during 1909-2010 (Zhao P. *et al.*, 2014). The temperature increase varied based on seasonal and geographical factors. The warming rate in winter was 0.04°C per year while it was 0.01°C per year in summer, and the north warmed more quickly than the south during 1960-2010 (Piao *et al.*, 2010). According to data from 520 meteorological stations in China, during 1951-2005 both the accumulated temperature (≥10 °C, ≥0 °C) and its value increased (Miao *et al.*, 2009). The annual effective accumulated temperature (≥10 °C), which is the sum of the temperature value between mean daily temperature and 10 °C for the whole year, generally has an increasing trend after 1985 (Liu S.H. *et al.*, 2013). Since the 1990s, the whole Soil-Burying Line of China, which indicates areas with average annual minimum temperature below -15 °C and with the necessity to have vine soil-burying in winter, has advanced northward, leaving

Table 2. Climate variables for viticulture.
(Source: Amerine and Winkler, 1944; Jones and Davis, 2000; Jones, 2005; Jones, 2007; Szymanowski *et al.*, 2007; Li H., Li and Yang, 2009; Li H., Wang *et al.*, 2009; Green and Szymanowski, 2012.)

Variable	Range of values		Class name or variety
Average Growing Season Temperature (°C) in viticulture (Jones, 2007)	13-15		Cool temperature
	15-17		Intermediate temperature
	17-19		Warm temperature
	19-24		Hot temperature
Sum of Active Temperature (SAT) from 1st April to 31st October in the northern hemisphere in viticulture (Jones and Davis, 2000; Szymanowski *et al.*, 2007; Green and Szymanowski, 2012)	2000-2200		Very early ripening
	2200-2500		Early ripening
	2500-2700		Moderately early ripening
	2700-2900		Late ripening
	>2900		Very late ripening
Effective Accumulated Temperature (EAT)/ Growing Degree Days (GDD) from 1st April to 31st October in the northern hemisphere in viticulture (Amerine and Winkler, 1944; Li H., Li and Yang, 2009)	°C	°F	
	<1371	<2500	Very early maturing grape varieties
	1372-1649	2501-3000	Early maturing grape varieties
	1649-1927	3001-3500	Late maturing grape varieties
	1927-2204	3501-4000	Acid grape varieties
	>2205	>4001	Very acid grape varieties
Frost-Free Period (FFP) (days) in viticulture (Jones, 2005; Li H., Wang *et al.*, 2009)	<160		Unsuitable region
	160-220		Suitable region
	>220		Suitable region but wine quality affected

vast areas (including some part of Xinjiang) suitable for viticulture without the necessity to have vine burying in winter (Li H., Wang *et al.*, 2007).

From the literature review (Table 3), we can observe a trend of increasing temperature in eight wine-producing provinces (Ningxia, Xinjiang, Shandong, Tianjin, Jilin, Gansu, Hebei, Shaanxi) and an increasing number of days with specific annual active accumulated temperature (≥0 °C, ≥5°C, ≥10 °C) in seven wine-producing provinces (Ningxia, Xinjiang, Shaanxi, Heilongjiang, Gansu, Hebei, Tianjin) over a long period (more than 40 years). Although the literature review does not cover all of the wine-producing provinces, we can see the correlation with the national trend of increasing annual mean

Table 3. Temperature change in Chinese wine-producing provinces.

Climate variable	Period	Region	Tendency	References	Possible benefits	Possible harms
Temperature	1961-2004	Ningxia	Annual mean temperature ↑ Mean temperature of each season↑	Chen X.G. *et al* ., 2008a	Current cold areas may be suitable to grow grapes that can only grow in warm areas (Moriondo *et al*., 2013). The ripening process accelerates (Holland and Smit, 2010). Less frost events(Jones, 2007). The sugar content increases for some grape varieties in some regions (Mozell and Thach, 2014). The acidity of grape decreases for some grape varieties in some regions (Mozell and Thach, 2014). The alcohol content increases for some grape varieties in some regions (Mozell and Thach, 2014).	The quality and yield of grape may be influenced (Fraga *et al*., 2012; Nicholas and Durham, 2012). The sugar content increases for some grape varieties in some regions (Mozell and Thach, 2014). The acidity of grape decreases for some grape varieties in some regions (Mozell and Thach, 2014). The alcohol content increases for some grape varieties in some regions (Mozell and Thach, 2014). Higher risk of pests and diseases (De Orduña, 2010). Impede photosynthesis and hence respiration process (Ashenfelter and Storchmann, 2016). Fruit burnt (De Orduña, 2010; Hadarits *et al*., 2010). Extreme heat threatens grape survival (Nicholas and Durham, 2012). Higher risk of fire (De Orduña, 2010).
	1960-2009		Frequency of extreme hot days ↑ Frequency of extreme cold days ↓	Zhang M.J. *et al*., 2012		
	1961-2010	Xinjiang	Degree of extreme cold days ↓ Mean temperature of January↑	Pu *et al* ., 2014		
	1950-2009	Shandong	Annual mean temperature ↑	Zhang S.P. *et al*., 2011		
	1955-2007	Tianjin		Liu S.M. *et al*., 2009		
	1961-2010	Jilin		Shen *et al*., 2014		
	1961-2010 1961-2003	Gansu	Annual mean temperature increased 0.29 °C per decade↑	Deng *et al*., 2012		
	1956-2007	Hebei	Annual mean temperature ↑ Mean temperature of each season↑	Liu F.Y. *et al*., 2014		
	1960-2013	Shaanxi		Wang Y.H., 2014		
Annual Active Accumulated Temperature	1961-2005	Ningxia	Annual number of days (≥0 °C , ≥10 °C) ↑	Zhang Z. and Lin, 2008	Longer favorable growth period (Holland and Smit, 2014). More areas may be suitable for grape planting (Li H. *et al*., 2007a; Li H. *et al*., 2007b). The ripening process accelerates (Holland and Smit, 2010). Grape yield may be increased by suitable heat (Jones, 2007).	The quality of grape may be influenced (Jones, 2007; Holland and Smit, 2014). Grape yield may be decreased by excess heat (Jones, 2007). Extreme heat may damage the vine (Holland and Smit, 2014).
	1961-2010	Xinjiang	Annual number of days (≥0 °C) ↑	Pu *et al*., 2013		
	1961-2008	Shaanxi	Annual number of days (≥5 °C) ↑	Wang Y.R. *et al*., 2011		
	1961-2005	Heilongjiang	Annual number of days (≥10 °C) ↑	Ji et al., 2009		
	1961-2003	Gansu	Annual Active Accumulated Temperature (≥0 °C, ≥10 °C) ↑	Liu D.X. *et al*., 2005		
	1956-2007	Hebei		Liu F.Y. *et al*., 2014		
	1955-2007	Tianjin		Liu S.M. *et al*., 2009		

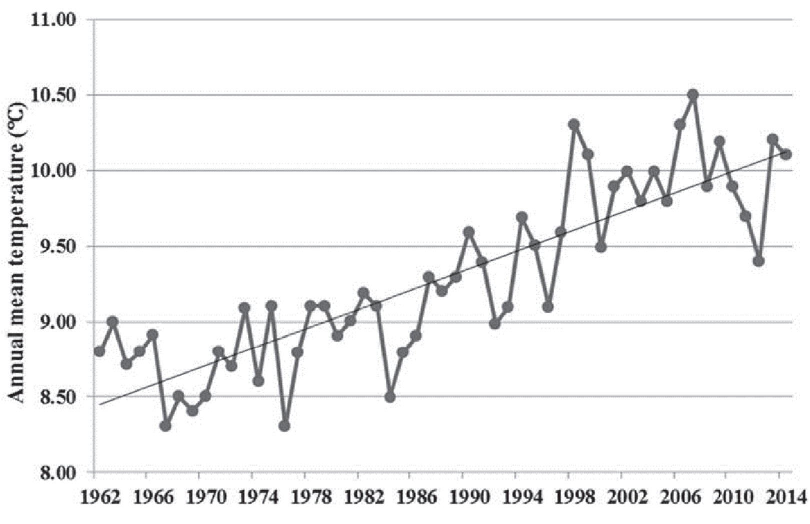

Figure 3. Annual mean temperature of China. Source: China Meteorological Administration, 2015.

temperature (Figure 3). These changes may have caused possible benefits such as an increase in the number of areas suitable for wine grape planting and possible harms such as a reduction in grape and wine quality (Table 3).

PRECIPITATION AND WATER SCARCITY

The precipitation trends have shown distinctive regional and seasonal variations, but there has been a general decreasing trend throughout the entire country. From 1960 to 2010, three periods of precipitation transitions occurred in the 1970s, 1980s and 1990s, and the increase and decrease of precipitation moved along with the latitude (Zhao H.R., 2013 ; Wang Y.J. and Yan, 2014). While southern China has experienced an increasing trend of rainfall in summer and winter, northeastern China has experienced a significant decrease of precipitation in summer and winter (Piao *et al.*, 2010 ; Li R.L. and Shu, 2013).

Approximately 98 % of the surface water in China is recharged by precipitation (Jiang, 2009). From precipitation data of the primary wine regions in 2010 (Figure 4), we can see that the majority of regions have lower precipitation amounts than the national level. In Ningxia, Gansu and Xinjiang, the annual mean precipitation is considerably less than the national level. Changes in precipitation have been observed over long periods (more than 40 years) in six wine-producing provinces (Ningxia, Tianjin, Shandong, Gansu, Shaanxi, Hebei) with decreasing annual amount of precipitation or decreasing annual precipitation days (Table 4). These changes may have positive impacts, such as fewer pests and diseases. However, the changes may also have negative impacts, such as increased drought frequency and increased irrigation cost (Table 4).

In 2013, China ranked 102nd of 176 nations and regions with 2083 cubic meter water resource per capita (World Bank, 2015). This ranking was lower than in many wine-producing countries (Figure 4). With the exception of Heilongjiang, Jilin, Xinjiang and Yunnan, the available water per capita in the other main wine-producing regions is lower than the national average. Xinjiang has vast amounts of water stored in glaciers. Yunnan has an uneven distribution of precipitation, and irrigation is difficult due to the

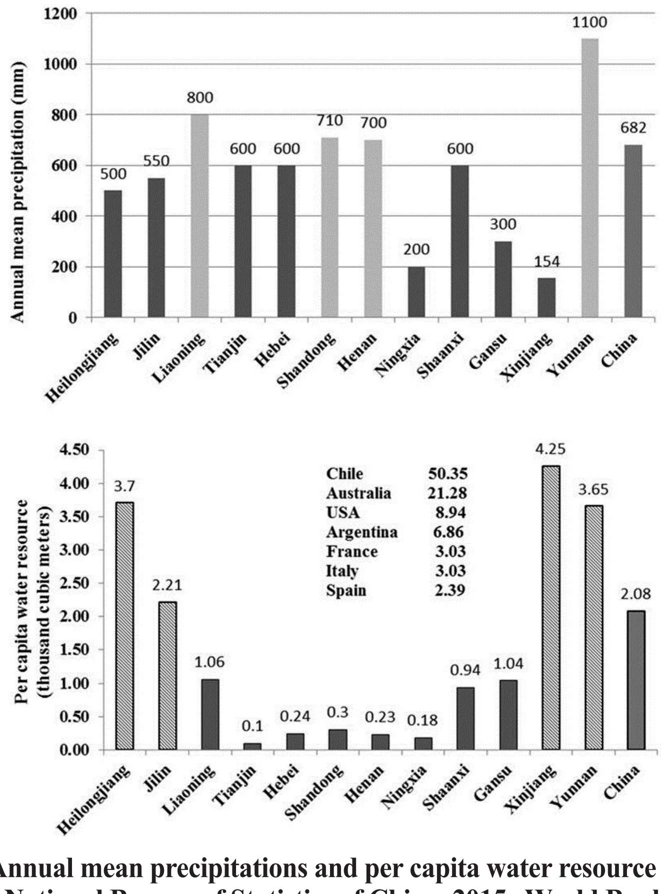

Figure 4. Annual mean precipitations and per capita water resource of China. Source : National Bureau of Statistics of China, 2015 ; World Bank, 2015.

Table 4. Precipitation change in Chinese wine-producing provinces.

Climate variable	Period	Region	Tendency	References	Possible benefits	Possible harms
Precipitation	1961-2005 1971-2011	Ningxia	Annual precipitation ↓	Chen X.G. *et al.*, *2008b*; Tan *et al.*, 2014	The grape growing condition over humid areas may be improved (Jones, 2007).	Higher frequency of drought disaster (Fraga *et al.*, 2012).
	1958-2007	Tianjin	Annual days of precipitation ↓	Li C. *et al.*, 2010	Less pest and disease damages (Fraga *et al.*, 2012).	Higher cost of irrigation and facilities (Jones, 2007).
	1961-2010	Shandong	Annual days of precipitation ↓	Dong *et al.*, 2014	The taste of some grapes may be improved (Fraga *et al.*, 2012).	Grape yield decreases (Lereboullet *et al.*, 2013).
	1961-2010	Gansu	Annual precipitation ↓	Deng *et al.*, 2012		Grape grows slowly (Fraga *et al.*, 2012).
	1960-2013	Shaanxi		Wang Y.H., 2014		Lower grape survival (Jones, 2007).
	1961-2011 1956-2007	Hebei		Xiang *et al.*, 2014; Liu F.Y. *et al.*, 2014		

obstruction of high mountains, all of which lead to water scarcity.

FROST-FREE PERIOD

Chinese studies indicate that between 1964 and 2003, in China, the acreage with a FFP above 160 increased significantly, especially between 1984 and 2003, while the First Frost Day (FFD) was delayed and the Last Frost Day (LFD) was advanced (Li H., Wang *et al.*, 2007; Li H., Wang *et al.*, 2009). The Yongning County, which is bordered by the Yellow River to the west and the Helan Mountain to the east, is one of the main wine-producing regions of Ningxia. Meteorological observations between 1952 and 2013 in Yongning County indicate that the FFP had an increasing trend (164 days in 1952 and 189 days in 2013) and the FFD was delayed (26th Sep in 1952 and 16th Oct in 2013) (Figure 5).

In eight wine-producing provinces (Shandong, Ningxia, Shaanxi, Xinjiang, Liaoning, Jilin, Heilongjiang, Tianjin), studies had indicated the increasing trend of FFP over 50 years, delayed FFD, and advanced LFD (Table 5). This finding may provide an opportunity for cultivation of more grape varieties and lead to more areas suitable for viticulture. However, grape quality and grape yield may be affected (Hadarits *et al.*, 2010; Fraga *et al.*, 2012) (Table 5).

EXTREME CLIMATE EVENTS

With the changing climate, there has been an increasing trend in periods of remarkable drought and flood, leading to challenges to agriculture and the Chinese wine industry. The most significant droughts appeared in 1978 and 2000, strongly affecting the crop production in China. Figure 6 indicates total agricultural crop area covered (crop yield loss >10%) and affected (crop yield loss >30%) by drought and flood in China from 1950 to 2014. In the 1990s and 2000s, strong floods caused by heavy rains impacted the entire country. In 1991, 1998, 2003, and 2010, serious floods hit China, leaving vast crop areas affected by flood (Figure 6).

Regionally, increased incidence of extreme rainstorms in Ningxia, Hebei and Xinjiang over a long period may have alleviated the drought problem but may have also increased the risk of flood damage and vineyard destruction (Table 6). Due to the increased severity of drought conditions in five wine-producing provinces (Ningxia, Liaoning, Shaanxi,

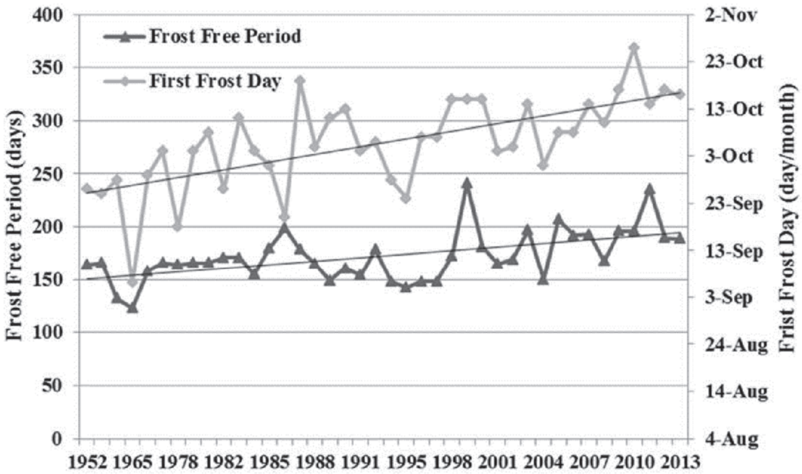

Figure 5. Frost-Free Periods and First Frost Day change in Yongning County, Ningxia, 1952-2013. Source: Ningxia Statistical Yearbook, 1985-2013.

Table 5. Provincial Frost-Free Period change.

Climate Variable	Period	Region	Tendency	References	Possible Benefits	Possible Harms
Frost-Free Period	1961-2008	Shandong	Number of frost-free days ↑ FFD was delayed LFD was advanced	Wang H.Y et al., 2011	More types of grape could be planted (Belliveau et al., 2006). More areas may be suitable for grapes (Belliveau et al., 2006). Less damage to buds and vine (Belliveau et al., 2006; Hadarits et al., 2010).	Grape quality may be affected (Fraga et al., 2012). Grape yield may be affected (Hadarits et al., 2010).
	1961-2010	Ningxia		Zhang L. et al., 2013		
	1961-2010	Shaanxi		Bai et al., 2013		
	1960-2011	Xinjiang		Pan et al., 2013		
	1957-2006 1961-2012	Liaoning		Li J. et al., 2010 Hu et al., 2015		
	1961-2012	Jilin		Hu et al., 2015		
	1961-2012	Heilongjiang		Hu et al., 2015		
	1955-2007	Tianjin		Liu S.M. et al., 2009		

Henan, Yunnan), an increased investment in irrigation infrastructure may be required.

In Ningxia, Xinjiang, Shaanxi and Yunnan, changes in the density and frequency of fog over more than 40 years may have impacted the growth process of grapes. In Ningxia, Tianjin, Hebei and Yunnan, the decreasing frequency of hail may have reduced the damage to vineyards.

CLIMATE CHANGE ADAPTATION STRATEGIES FOR THE CHINESE WINE INDUSTRY

Adaptation strategies can reduce the impacts of climate change and are a major challenge for viticulturists for the coming decades (Van Leeuwen *et al.*, 2007; Iglesias *et al.*, 2012; Ren *et al.*, 2013; Ollat and Touzard, 2014b). Climate change adaptation can be planned at the regional, national, and international level. We provide recommendations to the wine industry for adaptation strategies based on current Chinese climate change policies and studies of wine and adaptation (Figure 7).

1. Policy strategies

In recent years, there have been changes in Chinese government policy to support agriculture in adapting to climate change. China has promulgated a series of laws to promote agricultural development addressing the importance of sustainable water use (China's

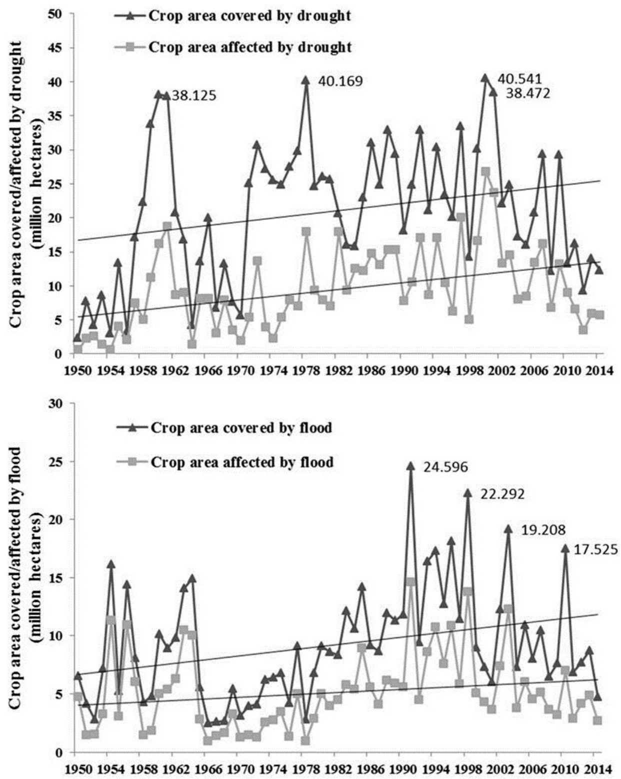

Figure 6. Crop area covered/affected by drought/flood in China.
Source: China Flood and Drought Management, 2009; National Bureau of Statistics of China, 2015.

Policies and Actions for Addressing Climate Change, 2008). It is necessary to establish and improve the laws pertaining to agriculture (China's Policies and Actions for Addressing Climate Change, 2012). The "12th Five-Year (2011-2015) Plan for the Wine Industry of China" has emphasized the importance of sustainability in the development of the Chinese wine industry.

There have also been efforts to address climate change adaption at the regional level, particularly in the Ningxia Province. The climate change situation and challenges in Ningxia have been analyzed and an adaptation and mitigation plan highlighting the urgency to take actions has been proposed (Scheme of Adaptation for Climate Change in Ningxia, 2009). The first wine regional protection regulation of China was approved in Ningxia in 2012 and was intended to ensure an environmental protection for the grape growing/wine-producing regions (Regulation on the protection of Eastern Foot of Helan Mountain Wine Region in Ningxia Hui Autonomous Region, 2012).

However, climate change adaptation legislation targeting the wine industry should be further established and implemented at the national and regional level (China's National Climate Change Programme, 2007).

2. Financial strategies

The Chinese government has invested over 20 billion Yuan in disaster prevention and mitigation capabilities and 1 billion Yuan in dry land water-saving agriculture (China's Policies and Actions on Climate Change, 2014). During the period from 2001 to 2005, the government invested more than 2.5 billion Yuan for climate change-related scientific and technological work (China's Policies and Actions for Addressing Climate Change, 2008). The investments increased to 7 billion Yuan during 2006-2010, and there have been continued increases since. Adequate financial support such as facility investment, agricultural insurance and subsidy for both industrial development and climate change adaptation will be essential for continued growth and development of the grape planting and wine-producing regions of China.

Table 6. Provincial extreme climate events and effects on viticulture.

Climate Event	Period	Region	Tendency	References	Possible Benefits	Possible Harms
Extreme Rainstorm	1961-2005 1961-2010	Ningxia	Annual days of extreme rainstorm ↑ Intensity andamount ↑	Chen X.G. *et al.*, 2008b; Li X. *et al.*, 2013	Alleviated drought problem (Battaglini *et al.* 2009; Fraga *et al.*, 2012).	Greater frequency of flood damage and loss of soil nutritic (Fraga *et al.*, 2012). Destruction of vineyards and more damaged roots and branches (Battaglini *et al.*, 2009). Damage to pollination and frui set (Belliveau *et al.*, 2006).
	1961-2005	Hebei		Gao et al., 2009		
	1901-2010	Xinjiang	Annual frequency of rainstorm ↑	Sun et al., 2011		
Drought	1951-2000	Ningxia	Frequency of drought ↑	Liang *et al.*, 2007	The grape growing conditions over humid areas may be improved (Battaglini *et al.* 2009; Fraga *et al.*, 2012; Holland and Smit, 2014). Less pest and disease damages (Holland and Smit, 2014). Improves the taste of some grapes (Holland and Smit, 2014).	Higher cost of irrigation and facilities (Battaglini *et al.*, 200(Fraga *et al.*, 2012). Decreased grape yield (Hadarit *et al.*, 2010; Ollat *et al.*, 2016). Reduced grape growth (Fraga ε *al.*, 2012). Threat to grape survival (Holland and Smit, 2014).
	1961-2004		Especially in winter frequency of drought ↑	Sang *et al.*, 2007		
	1978-2010		Degree of drought ↑ Geographical distribution of drought ↑	Tan *et al.,* 2014		
	1988-2007	Liaoning	Degree of drought ↑	Zhao X.L. *et al.*, 2009		
	1961-2010	Shaanxi		Cai *et al.*, 2013		
	1961-2008	Henan		Zhang H.W. *et al.*, 2009		
	1961-2011	Yunnan	Degree and time duration of drought↑	Zhang W.C.*et al.*, 2013		
Fog	1961-2009	Ningxia	Annual frequency in the north ↑	Zhou *et al.*, 2010	Supplements water and keeps ground heat (Calwineries, 2017). Moderate it can protect grapes from extreme heat (Wine-searcher, 2017).	May impede the photosynthesi process and hence respiration (Progressive viticulture, 2016).
	1961-2003	Xinjiang	Annual frequency after 1987↓	Ma *et al.*, 2005	Fewer obstacles for photosynthesis and respiration (Progressive viticulture, 2016).	
	1960-2010	Shaanxi	Annual frequency after 2000↓	Zhang H.F. *et al.*, 2013		
	1961-2008	Yunnan	Annual frequency↓	Tao *et al.*, 2011b		
Hail	1961-2004 1961-2010	Ningxia	Annual frequency of hail ↓	Wu *et al.*, 2008; Yang *et al.*, 2012	Lower frequency of hail damage (Fraga *et al.*, 2012).	
	1979-2008	Tianjin		Min *et al.*, 2012		
	1979-2008	Hebei				
	1961-2008	Yunnan	Annual and seasonal frequency↓	Tao *et al.*, 2011a		

3. Technical strategies

Water resources are essential for viticulture. Chinese policy has provided several technological measures to enhance the efficiency of water consumption in agriculture (China Water Conservation Technology Policy Outline, 2005). Low carbon agriculture should be promoted and agricultural waste should be recycled for sustainable agriculture. Additionally, additional irrigation facilities should be built and existing facilities should be improved in order to conserve water. It is also proposed that when crops and farming systems are chosen, climate change should be taken into consideration. The need to develop high-quality stress resistant crop varieties is also addressed (China's National Plan on Climate Change 2014-2020, 2014). Furthermore, management practices of pests and diseases should be adapted to new strains or new pathogens (Goulet, 2014).

Climate-based zoning has been attempted for viticulture in order to guide grape planting and wine production. In Xinjiang and Ningxia, the viticulture climatic zoning classification system uses three indexes : FFP, dryness index (from April to September) and mean lowest temperature below -15 °C (Wolf and Boyer, 2003 ; Tonietto and Carbonneau, 2004 ; Wang H. *et al.*, 2010 ; Li H., Wang and Wang, 2011). In the Shaanxi and Jingjintang area, which includes Beijing, Tianjin and some areas of Hebei, the amount of precipitation from July to September is used as an index (Li H. and Meng, 2009 ; Li H., Lan and Wang, 2011). Tonietto and Carbonneau (2004) have provided a Multicriteria Climatic Classification System (Géoviticulture MCC System) for worldwide grape and wine zoning based on classes for three indices : dryness index (DI), heliothermal index (HI) and cool night index (CI). These indices are representative of worldwide viticultural climate variability and are related to the requirements of varieties, vintage quality and typicity of wines. They were calculated to evaluate the worldwide climate for viticulture in 97 grape growing regions from 29 countries

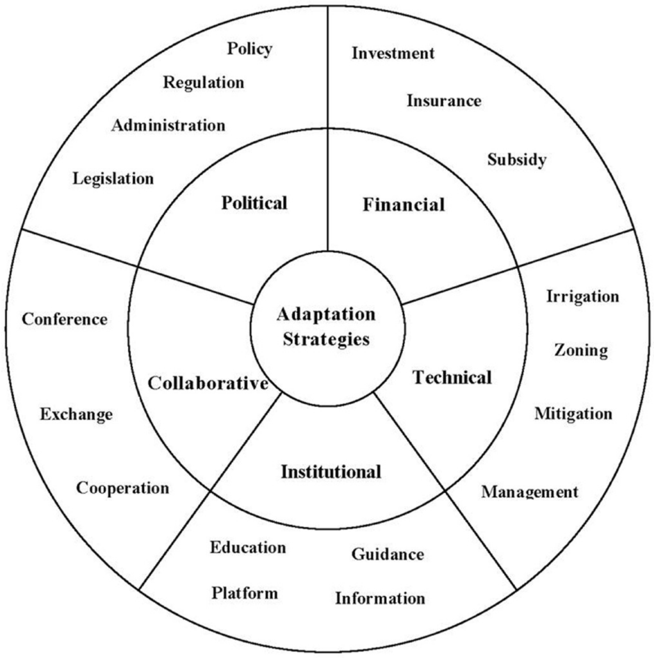

Figure 7. Adaptation strategies for the Chinese wine industry. Source: Own elaboration.

including China. Combining grape zoning methodology with climate change simulations such as climate change scenarios can enhance viticulture adaptation for the future. To deal with the uncertainties of future climatic simulations in climate change impact studies, different climatic scenarios and downscaling methods should be considered (Caubel *et al.*, 2014). Integrated models such as ecophysiological model and the MILA-STICS model can predict complex impacts for climate change (Caubel *et al.*, 2014; Piéri and Lebon, 2014). Multi-scale climatic approaches such as the ANR-TERVICLIM and GICC-TERADCLIM research programmes, which intend to observe and simulate climate and climate change at local scale, can produce a scale assessment of climate change impacts in different wine-producing regions worldwide (Quénol and Bonnardot, 2014).

Mozell and Thach (2014) have provided vineyards and wineries with a series of practical solutions for adapting to climate change. Fifteen solutions for vineyards are provided to offset rising temperatures, water shortages, increases in heat, drought and light intensity and their impacts such as earlier maturation, and increases in the number of pests. Eleven solutions are provided to enhance wine production in order to offset warmer temperatures, increases in sugar and alcohol levels, reduction in acidity, vintage variability, and earlier harvest and ripening.

Further research is needed to assist the Chinese wine industry in adapting to climate change. An interdisciplinary approach will be needed that incorporates improvements in grape resistance, new grape planting and wine making technology, disaster response, climate change adaptation management and social and economic evaluation.

4. Institutional strategies

Institutional changes are indispensable for effective adaptation solutions (Ollat and Touzard, 2014a; Ollat and Touzard, 2014b). The Chinese government has strongly promoted an awareness and understanding of climate change impact in general, but a stronger focus is needed on how climate change impacts the wine industry in particular. The broadcast of climate change knowledge and adaptation for wine producers and wine traders can be promoted by media, materials, forums, campaigns and training during which regional wine associations in China can participate. Wine institutes in universities can assume the responsibility for educating the public. Electronic platforms can be established to broadcast and share information.

5. Collaborative strategies

Climate change demands the attention of the global wine industry. The World Conference on Climate

Change and Wine has been organized three times by the Wine Academy of Spain to address the need for climate change adaptation in viticulture (Li Y.B., 2015). Several investigations of climate change and viticulture are underway in France and other wine-producing countries (Ollat and Touzard, 2014b; Yzarra *et al.*, 2015). In France, the multidisciplinary LACCAVE project (long-term adaptation to climate change in viticulture and enology) involving 23 different laboratories from the National Institute for Agricultural Research of France (INRA), the National Center for Scientific Research (CNRS) and several French universities aims to analyze the impacts of climate change on viticulture and wine and to assess current and design future adaptation strategies (Ollat *et al.*, 2016). With a goal to establish a scientific framework addressing climate change issues in viticulture, this project is organized in seven areas: characterization and perception of climate change; physiological and genetic bases of grapevine adaptation to climate change; development of technical innovations for adaptation to climate change; evaluation of the impact of technical innovation at a territorial scale; analysis of the evolution of economic strategies; data management and analysis; and elaboration of strategic scenarios for 2050 (Ollat and Touzard, 2014b). The importance of communication and cooperation with developed countries and international organizations has been highlighted (China's Policies and Actions for Addressing Climate Change, 2015). As China moves from the insular policies of the past to increased communication and sharing of technology at the international level, the Chinese wine industry will greatly benefit.

CONCLUSIONS

In the last several years, domestic wine production has experienced a dramatic increase in China, boosted by rising consumption and a favorable economic situation. This increase faces important future challenges, a number of them emerging from the impacts of climate change, which may affect the quantity and quality of the wine production and even the vineyard location.

The analysis of the climate trend in China, which is focused on variables with climate relevance to viticulture, exhibits inconsistent effects, and confirms the relevance of the changes in the primary wine-producing regions.

The literature suggests a general tendency of increasing temperatures and accumulated temperature, water scarcity with higher frequency of extreme events and increasing number of frost-free days, all of which will bring both challenges and opportunities to the young Chinese wine industry.

The identified effects indicate the need for more research at the regional level for an accurate assessment of climate change impact on the Chinese wine industry and a proper design of adaptation measures, considering the specific needs and characteristics of wine production. These specific adaptation measures have to be implemented under the national framework of climate change adaptation and need to consider the coordination of policy, financial, technical, institutional and collaborative strategies.

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Which climatic modeling to assess climate change impacts on vineyards?

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Abstract

Abstract: The impact of climatic change on viticulture is significant: main phenological stages appear earlier, wine characteristics are changing... This clearly illustrates the point that the adaptation of viticulture to climate change is crucial and should be based on simulations of future climate. Several types of models exist and are used to represent viticultural climates at various scales. In this paper, we propose a review of different types of climate models (methodology and uncertainties) and then few examples of its application at the scale of wine growing regions worldwide.

Keywords: climate change, modelling, uncertainties, bioclimatic index, viticulture

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Introduction

The vine, like other perennial crops (fruit trees, forests), is particularly sensitive to climate change because its management and adaptation must be anticipated well in advance (van Leeuwen *et al.*, 2004, Carey *et al.*, 2008). The characteristics of vineyards and of the wines are the result of a combination of several factors (grape, soil, climate, agricultural practices) that produce wines with a typical style and quality that are distributed on specific territories (Webb *et al.*, 2007; Hall and Jones, 2010; Quénol *et al.*, 2014). The temperature increase over the last 50 years has led to the advance of the main phenological stages and a change of wine characteristics (sugar content and acidity) (Jones *et al.*, 2005; Webb *et al.*, 2008; van Leeuwen *et al.*, 2009). These main findings show that the adaptation of vineyards to climate change is crucial and should be based on simulations of future climate (Quénol et al, 2014; Moriondo et al, 2013, Hannah et al, 2013, Santos *et al.*, 2013).

Different types of model exist to represent climate on Earth at various scales. At the global scale, General Circulation Models (GCMs) are mainly used as the basis to build climate change scenarii that estimate trends in climate variables like temperature, rainfall and wind globally, at low spatial resolution (~300 km). Obviously, these kinds of models are not suitable for considering temperature variability at vineyard scale. Several studies have tried to improve the resolution of GCMs, leading to a range of different regional climate models, such as WRF (Weather Research and Forecasting, http://www.wrf-model.org/index.php). In the context of climate in vineyards, regional climate models have been used in the South African district of Stellenbosch to study effects of the local circulation (Bonnardot *et al.*, 2005; Bonnardot *et al.*, 2012; Soltanzadeh *et al.*, 2016), and are currently being used to characterize climate and model vine phenology in the Marlborough region, New Zealand (Sturman *et al.*, 2014) and in Burgundy (Xu *et al.*, 2012). In addition to regional models based on physics, downscaling techniques enable representation of climate at local scales on the basis of statistical relationships between global and local variables. However, the spatial resolution of these models is generally still not accurate enough to be used by winegrowers (Dunn *et al.*, 2015). To compensate for the difficulty that dynamic models have in accurately representing local temperature variability, some fine scale observation networks have been established to monitor temperatures. Their spatial distribution is designed on the basis of topographic features derived from Digital Elevation Models (DEMs). This relationship can be used to estimate temperatures at a very fine scale and then to provide a better analysis of plant response. In the context of vineyards, frost damage on grapevines can be very localized and is generally strongly connected to local topography (Quénol and Bonnardot, 2014; Irimia *et al.*, 2014; Madelin and Beltrando, 2005). Therefore, integration of high resolution monitoring networks and atmospheric models appears to be a promising approach.

As stated in Cautenet and Bonnardot (2014), climate models are complex computer programs that are able to simulate the climate of both the past and the future. Climate models and weather models use the same equations, which are the fundamental equations of atmospheric physics. Climate models include relatively simplified representations of the surface of the Earth and its atmosphere that take into account all the mechanisms that govern atmospheric circulation. They are able to predict the weather and to represent the climate, that is to say, the average state of the atmosphere over long periods. Depending on their applications, climate models have different spatial

Table 1. The spatial and time scales and areas of application of climate models (Cautenet and Bonnardot, 2014).

Climate models	Spatial resolution	Temporal resolution	Scale	Application
Global Circulation Models (GCM)	From 5° to 0.5° (500 to 50 km)	From 10 years to several hundred years	Global	Modeling of atmospheric general circulation Modeling of global warming
Global with varying resolution (VRGCM)	From 1° to 10-12 km	More than 10 years to several hundred years	Global and regional	Weather forecast Modeling of global warming
Regional Circulation Models (RCM)	From 50 km to 200 m (imbricated grids)	Hourly to several days	Regional and local	Weather forecast Meso-scale climate modeling

and temporal resolutions. Table 1 describes the key attributes of global and regional climate models.

Regional climate modeling

As mentioned above, the global climate models do not have a fine enough resolution for local scale impact studies. This is why many studies are attempting to create models able to disaggregate the overall climate signal at regional scales. Regional circulation models of the atmosphere, or mesoscale models, can represent finer resolutions than global models, of the order of a kilometer or even a few hundred meters. The meshes used in these models are fine enough to allow consideration of the consequences of changing human activities.

1. Regional atmospheric models

Regional atmospheric models aim to regionalize the outputs of global models by using nesting of model grids of increasing levels of resolution. The first grid is thus forced at its boundaries by atmospheric fields at low resolution, often from the global climate models, while the last grid contains the data with the finest resolution. These fine grids represent the regional circulation of the atmosphere models. With the improvement of the resolution of model outputs, topography, vegetation, hydrography and soil characteristics are better taken into account. Meteo-France uses the ARPEGE-Climate model as a global model, which has a variable resolution of 50 km over the Mediterranean and 450 km over the Pacific (Déqué *et al.*, 2007). To disaggregate the ARPEGE signal to finer scales, they use the regional ALADIN model down to a resolution of 10 km, which is also called a «limited-area model.» On the scale of Europe, the EuroCordex model output enables a resolution of a few kilometers (Vautard *et al.*, 2013) In terms of regional climate modeling, many studies have demonstrated the value of using different regional atmospheric models with increased resolution for characterizing climate variability and the potential climate risks in a wine-producing environment. The so-called physical atmospheric models is used to grasp the complexity of the environment (e.g. Earth-atmosphere models). The development of these models has grown strongly in recent years thanks to the increased computing capacity that allows improvements in both their resolution and complexity. The RAMS model (Regional Atmospheric Modeling System) (Pielke *et al.*, 1992)) was used to study the local circulations in the wine district of Stellenbosch in South Africa (Bonnardot *et al.*, 2005; Bonnardot and Cautenet, 2009; Soltanzadeh and al., 2016), Champagne and the Loire Valley (Briche *et al.*, 2014; Bonnefoy, 2012). Similar modeling studies have been conducted in Australia (Lyons and Considine, 2007). The WRF model (Advanced Research Weather Research and Forecasting) has been used to investigate the spatial variability of climate in Burgundy (Bonnefoy *et al.*, 2010. Cuccia, 2013; Xu *et al.*, 2012), as well as New Zealand (Sturman *et al.*, 2014). But, these models at very fine scales require a strong computing capacity.

2. Statistical modeling by data interpolation

The use of mesoscale atmospheric modeling allows a scalar disaggregation of spatial patterns obtained from global models, but the need for significant computing capacity makes it difficult to achieve satisfactory results at a very fine scale. The interweaving of various atmospheric phenomena in terms of the overlapping of scales (from local to synoptic) makes this type of modeling impracticable at a very detailed level. To overcome these limitations, advanced statistical methods are used to perform spatial interpolation of climate data obtained at fine scales. These methods are based on establishing the relationship between surface characteristics (e.g. landscape morphology and land use) and weather variables. In this type of study, the existence of a link between climate elements and topographic characteristics is then evaluated spatially across a study site using a Geographic Information System (GIS). Mesoscale numerical modeling and spatial interpolation of climate data have specific advantages and disadvantages. Numerical modeling at the mesoscale can take into account the synoptic scale weather as well as the overlapping scales, but it is difficult to use at fine scales particularly because of computing time and parameterization problems. Spatial interpolation using multiple regression has the advantage of being adapted to local scales, but the results are only a partial explanation because the model is static (with reference to a fixed time frame).

3. Uncertainties using climate data

In order to consider the uncertainties related to climate data several methods have been developed in the literature during last years:

- Anomalies method which calculates the difference between two periods (current and future conditions) for different climatic variables (ie. temperature, rainfall, wind) and apply it to the current conditions. This method is easy to be used but does not allow to introduce a change in variability

- Weather types method is a statistical method which classifies each day into a category of weather type (with its own structure). The main concern is then to be sure that the method generates correctly the future distribution of weather types. This method is very time consuming and needs very long observed past datasets;

- Quantile-quantile method is a statistical method. «*It consists in correcting the values of the model's quantiles by those computed from observations... This method has in particular the advantage of correcting the model bias*.» (DRIAS, *www.drias-climat.fr* ; Déqué, 2007).

The uncertainty in regional climate modeling in climate change context is complex because downscaling methods are all based on simulations of global climate model («cascade of uncertainties» from Boe, 2007). In order to illustrate this uncertainty, a multi-models approach for each RCP scenario was used about a regional climate study in France (Ouzeau *et al.*, 2014).

Climate modeling at the scale of wine regions

First studies of the impact of climate change on the grapevine have been conducted at multi-local scale. This approach has been used initially because of the past limitations on computing resources. Several studies in recent years have used this method to characterize the changing climatic conditions and production of European vineyards (Garcia de Cortazar Atauri-2006; Levrault and Brisson, 2010, Cuccia *et al.*, 2014). These studies describe changes in only some grid points across France (i.e. 8-20 points). Even if the methodology does not allow to represent spatial distribution of changes, it allows to multiply the number of hypotheses (different soil types, varieties and cropping systems) to achieve a more detailed analysis of the future impacts and to define adaptation strategies.

The provision of regionalized climate data from climate models of the latest IPCC reports (2014) (Coupled Model Intercomparison Project, CMIP 4 and 5), has allowed to map climate variability in connection with the evolution of the potential viticulture areas (past, present and future).

Most recent work has been based on calculations of bioclimatic indexes based on different climatic models and scenarios of climate change (Moriondo *et al.*, 2013; Santos *et al.*, 2013, Hannah *et al.*, 2013). These studies showed significant potential changes on the distribution of vineyards.

The warming trend is often reflected by increased bioclimatic indices, which may involve a change in the classification of wine climate types from one category to the next. For example, Santos *et al.* (2013) analyzed past climatic conditions mapping several bioclimatic index (Huglin, Winkler, Dryness indices) between the 1980-2009 and 1950-1979 periods across all of Europe and North Africa. In some regions, particularly the north and east of Europe, an increase in the values of these indices is favorable and allows these regions to benefit from improved conditions for growing vines, while in other regions (mainly southern Europe) the increase in index values is more detrimental.

Recent studies also evaluate these trends under future climatic conditions (Moriondo *et al.*, 2013; Hannah *et al.*, 2013). These studies suggest three quite different trends in Europe until 2050. First, wine production in the southernmost Mediterranean regions could be adversely affected by 2020. Second, there is an intermediate zone for which the different studies show fairly divergent and sometimes contradictory results. This area is from the vineyards of northern Spain, Italy and Greece to the vineyards of the Loire Valley, Alsace and Germany. Third, to the north of these vineyards a general improvement of climatic conditions for the cultivation of vines is predicted. This could allow an expansion of the current production area if it is worthwhile from an economic point of view. By 2050, the various scenarios studied do not show strong differences, and the three trends described above are partly independent of the socio-economic model chosen by the industry. In contrast, over the period 2070-2100 wine producers can expect a significant change, resulting in a major transformation of European vineyards, and a sharp reduction in production areas in Mediterranean wine producing area.

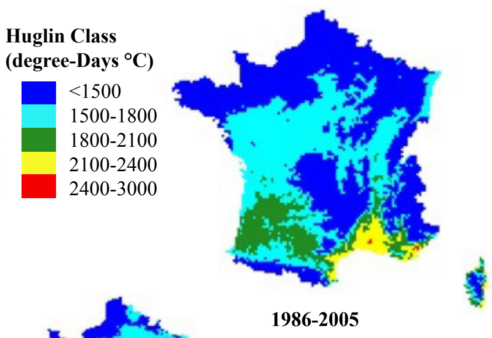
All these results are confirmed by a recent study realized in France by the LACCAVE project. In this study, the Huglin index[1] (Figure 1) was mapped using data from the Aladin regional model (spatial resolution of 8 km). The maps were produced for the periods 1986-2005, 2031-2050 and 2081-2100 based on three Representative Concentration Pathways (RCPs) for four greenhouse gas concentrations (2.6, 4.5 and 8.5). Over the period 1986-2005, the northernmost wine regions (Loire Valley, Champagne, Alsace, Burgundy) correspond to the «cold» class. Bordeaux vineyards are in the «temperate» class and southern vineyards are mainly in the «warm temperate» class. For the 2031-2050 period, according to the RCP2.6, 4.5 and 8.5 scenarios, we can see a northward shift of the classes over France with the transition to the next class in southern wine regions. This is the case for the

[1] Huglin index is related to the thermal requirements of grape varieties, and to potential sugar content of grapes (Huglin and Schneider, 1998).

Bordeaux region that will theoretically increase from the «temperate» class to «warm temperate»; Burgundy, the Loire Valley and Alsace from the «cold» class to the «temperate» class and Languedoc from «temperate/temperate warm» to «temperate warm/warm». For the 2081-2100 periods, this potential migration (of zones of specific wine style) will become more important through the transition to the «warm» class for most wine regions, according to the RCP6.5 and 8.5 scenarios. Although these maps were made from modeled data, the results illustrate the range of possible trends (depending on the scenario) in the evolution of French viticulture and can help stakeholders to make decisions about future strategies.

Finally, Santos *et al.* (2016) have used recent data from Euro-cordex project to simulate the future phenology, production and water and nitrogen stress of grapevine systems in Europe using the STICS crop model (Brisson *et al.*, 2009). Authors only used a mean year (average year of 30 years of data) of

Class	°C	Examples
Very warm	IH > 3000	São Francisco Valley (Brazil)
warm	2 400 ≤ IH ≤ 3000	Malaga (Spain) Marsala (Italy)
Warm temperate	2 100 ≤ IH ≤ 2400	Napa (USA) Montpellier (France)
temperate	1 800 ≤ IH ≤ 2100	Pau, Bordeaux (France)
cold	1 500 ≤ IH ≤ 1800	Colmar, Angers (France)
Very cold	IH ≤ 1500	Québec (Canada) London (England)



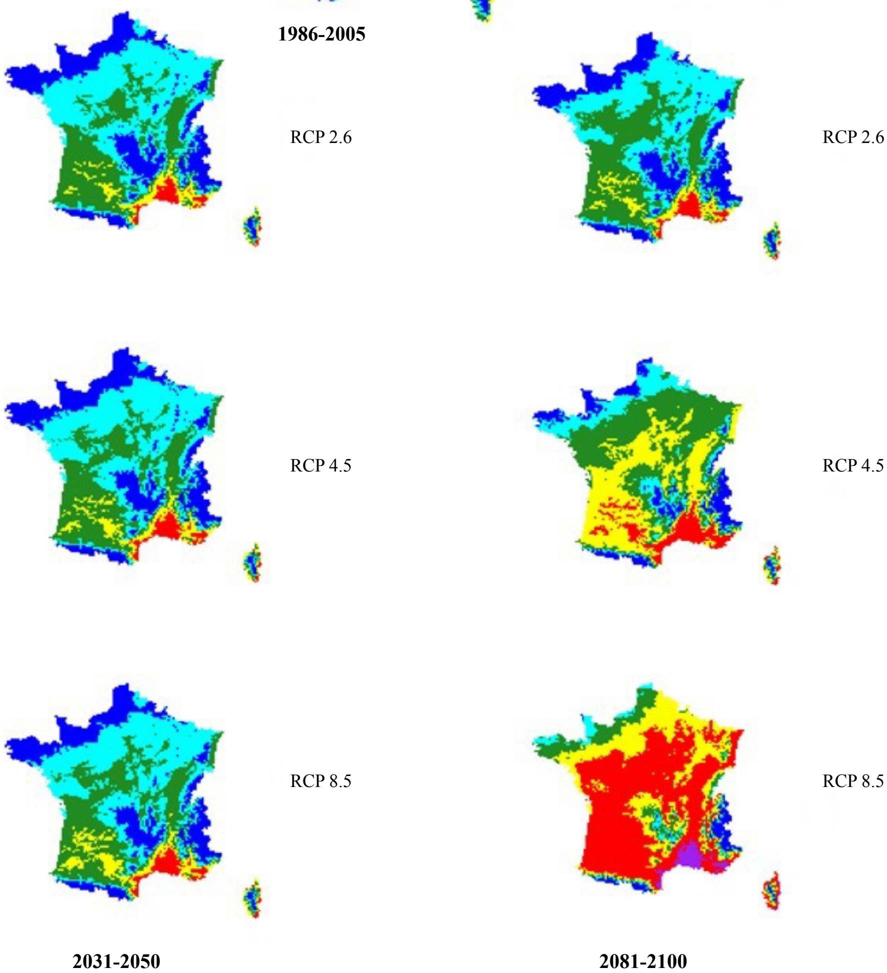


Figure 1. Mean Huglin Index classes through RCP scenarios. (sources: DRIAS)

each variable to simulate future conditions and they highlighted the importance to use several scenarios and methods to characterize these impacts. Several crop models simulating grapevine systems have been developed during the last years (Moriondo *et al.*, 2015) and will be useful in the future to describe and test adaptation strategies. In this context, the quality and the availability of climatic variables required (radiation, wind, humidity, water potential) to simulated plant processes will be very important.

Discussion and conclusion

The various studies describing the calculation of bioclimatic indices based on different models and scenarios of climate change should allow estimation of the future state of viticulture in different parts of the world, although not without some uncertainties. First, the model predictions themselves have a significant amount of uncertainty in that it is not possible to validate future results (only validation on past data). Second, the indices are merely bioclimatic indicators but not the only factors affecting the development of the vine. In response to the article by Hannah *et al.* (2013) showing a large decrease in the ability to continue viticulture in the well-established wine-producing regions of the world over the next forty years, van Leeuwen *et al.* (2013) argued that it was necessary to be very careful when drawing definitive conclusions from this type of analysis. These studies on the impact of climate change address potential changes in the major global wine regions, but few have attempted to observe and simulate the climate at the scale of a terroir (at the local scale). Little research has addressed the future impacts of climate change on agro-climatic potential at fine scales. Yet in some soils (especially in complex terrain), changes in atmospheric parameters are very important over relatively small areas (of the order of a few kilometers to a few meters) and the quality of grapes and wine is often related to these local characteristics (slope, soil, etc.). Observation and modeling at the fine scale must therefore be considered in the development of strategies for adapting to climate change impacts on vineyard and interactions with terroir (Quénol *et al.*, 2014).

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The application of high-resolution atmospheric modelling to weather and climate variability in vineyard regions

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Abstract

Grapevines are highly sensitive to environmental conditions, with variability in weather and climate (particularly temperature) having a significant influence on wine quality, quantity and style. Improved knowledge of spatial and temporal variations in climate and their impact on grapevine response allows better decision-making to help maintain a sustainable wine industry in the context of medium to long term climate change. This paper describes recent research into the application of mesoscale weather and climate models that aims to improve our understanding of climate variability at high spatial (1 km and less) and temporal (hourly) resolution within vineyard regions of varying terrain complexity. The Weather Research and Forecasting (WRF) model has been used to simulate the weather and climate in the complex terrain of the Marlborough region of New Zealand. The performance of the WRF model in reproducing the temperature variability across vineyard regions is assessed through comparison with automatic weather stations. Coupling the atmospheric model with bioclimatic indices and phenological models (e.g. Huglin, cool nights, Grapevine Flowering Véraison model) also provides useful insights into grapevine response to spatial variability of climate during the growing season, as well as assessment of spatial variability in the optimal climate conditions for specific grape varieties.

Keywords: WRF model, weather and climate, grapevine response, Marlborough, New Zealand

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Introduction

It is well known that the temporal and spatial variability of weather and climate within vineyard regions has an important influence on grapevine response and therefore wine production (quality and quantity). To understand the potential consequences of climate change for viticulture in regions of complex terrain it is important to investigate this influence across a range of time and space scales in order to appropriately manage future risks to the local wine industry. However, many vineyard regions have a poor record of meteorological, as well as phenological, observations. We therefore need to explore other ways of investigating the variation of weather and climate across wine-producing regions and its influence on the grapevine at the vineyard scale. Physics-based mesoscale atmospheric numerical models are tools that can be used to provide a good understanding of the fine-scale variability of weather and climate across a vineyard area, even in regions of complex terrain (Bonnardot and Cautenet, 2009 ; Soltanzadeh *et al.*, 2016). These models have been used to address a range of other applied problems, including dust and air pollution dispersion, wild fire behaviour and wind energy resource assessment (Purcell and Gilbert, 2015 ; Alizadeh Choobari *et al.*, 2012 ; Simpson *et al.*, 2013 ; Sturman *et al.*, 2011 ; Titov *et al.*, 2007).

The key research question addressed in this paper is therefore : what can mesoscale numerical models tell us about weather/climate variability at vineyard scale and its influence on grapevine response ? This question is addressed by applying an internationally well-known mesoscale atmospheric model to New Zealand's most important vineyard region.

Research methodology

The main feature of this research is the application of the Weather Research and Forecasting (WRF – Skamarock *et al.*, 2005) model to simulate local weather/climate in vineyard regions in complex terrain for both short term weather forecasting in support of frost protection and spraying activities, as well as longer term investigation of the spatial and temporal variability of vineyard scale climate. In the latter case, the aim is to demonstrate the usefulness of atmospheric mesoscale models for :

- identifying the major influences on local weather and climate (sea breezes, foehn effect, cold air drainage and ponding, etc.) in vineyard regions, essentially identifying the main contributions to the climate component of the terroir.

- investigating the influence of local and regional weather/climate on grapevine response and climate risk factors for viticulture through the coupling of mesoscale models with bioclimatic and crop models.

Marlborough region

Marlborough is the most important wine-producing region of New Zealand, producing more than 70 % of the wine exported from the country. It is located in the northeastern part of the South Island in a region of complex terrain, with significant relief and altitudes reaching more than 1500 m in a number of places (Figures 1 and 2). The main vineyard areas are mostly located on the lower-lying flood

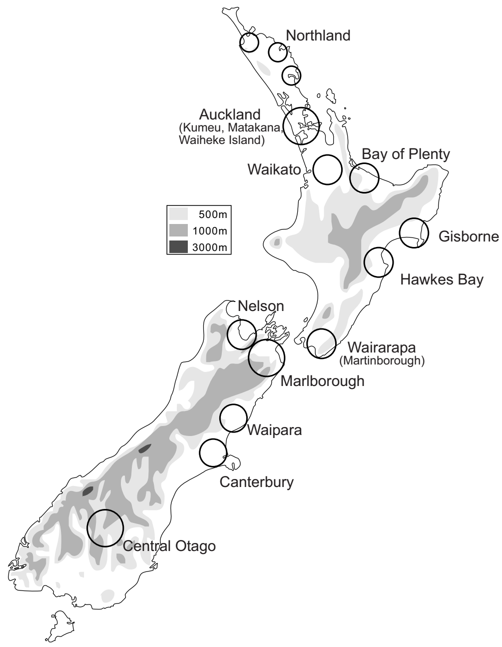

Figure 1 - The location of vineyard regions in New Zealand (after Sturman and Quénol 2013).
The size of the circles merely identifies the general locations of the vineyards.

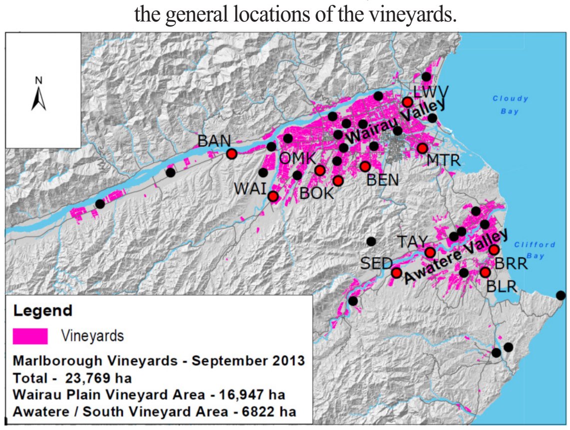

Figure 2 - Distribution of vineyards within the Marlborough region in 2011, with the locations of weather stations operating between 2013 and 2015.
The filled circles are sites of long-term records, these were supplemented by the red sites for the study period. Vineyard map provided by the Marlborough District Council.

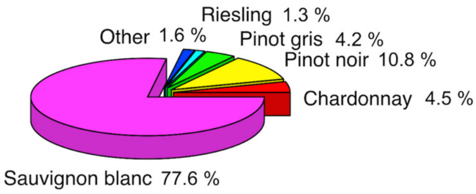

Figure 3 - The breakdown of vineyard area in the Marlborough region by grape variety in 2016.

plains of the two main valleys of the Wairau and Awatere rivers.

Sauvignon blanc is the dominant grape variety planted in the region, following by Pinot noir, Chardonnay and Pinot gris (Figure 3).

WRF model setup

The WRF was set up using a four-level nested grid configuration, as shown in Figure 4a, for computational efficiency. The model was run twice per day producing hourly predictions of meteorological parameters such as air temperature and pressure, wind speed and direction, and atmospheric humidity at 1 km resolution over the Marlborough region (Figure 4b).

Initial assessment of the WRF model performance through comparison with automatic weather station data in Marlborough suggests that there is a cold bias of between 0.5 and 1.0 °C. Potential cold bias of model predictions has previously been recognized (Steele *et al.*, 2014; Hu *et al.*, 2010), and needs to be allowed for when interpreting analysis of spatial patterns across the region. This cold bias will be the subject of further research so that appropriate adjustments can be made.

In addition to seasonal maps of key variables (average daily maximum, minimum and mean temperature), maps of accumulated degree-days were derived from hourly temperature predictions two metres above ground level

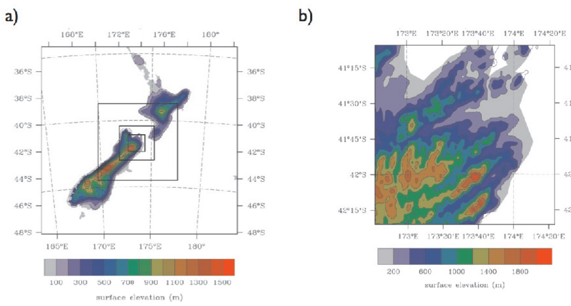

Figure 4 - The WRF nested grid configuration, showing terrain height, a) for all four grid domains (27, 9, 3 and 1 km resolution), and b) the high-resolution domain.

and the Grapevine Flowering Véraison (GFV) model (Parker *et al.* 2011, 2013), as shown in Figure 5. Seasonal maps of using the parameters of the GFV model for a temperature summation (base temperature of 0 °C, start date of 29 April) and other bioclimatic indicators were also produced.

It should be mentioned that the GFV model was not developed to provide a degree-day accumulation over the whole growing season, but to set temperature sum thresholds at which a given grape variety reaches a given phenological stage (flowering or véraison). Although the results produced here do not strictly reflect the original rationale of the GFV model, it is still possible to derive a temperature summation for the growing season (as shown in Figure 5), allowing analysis of inter-annual and intra-regional patterns of heat accumulation.

Results

1. Coupling WRF model output with bioclimatic indices

By coupling the WRF model output with bioclimatic indices and phenological models it is possible to provide a spatial analysis of the suitability of a vineyard region to a range of different grapevine varieties. As shown in Figure 6, the key indices/models examined in this paper are:

- Mean growing season temperature (1 October to 30 April);
- Huglin index (1 October to 31 March);
- Grapevine Flowering Véraison model (29 August to 30 April).

The three maps in Figure 6 show significant commonality. For example, the influence of the complex terrain of the region is clearly evident in all three maps, with altitude and distance from sea having an important influence on the thermal environment of the region. However, some

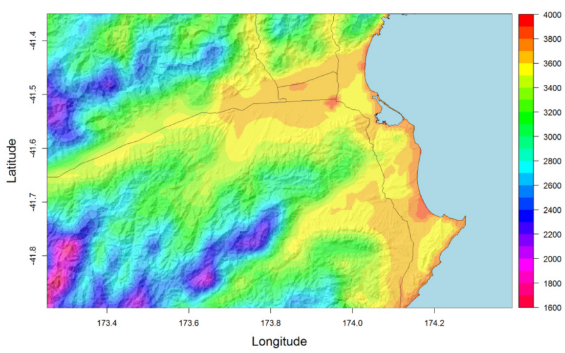

Figure 5 - Example map of temperature summation over the Marlborough region from 29 August 2013 to 30 April 2014 calculated according to the GFV model using a threshold of 0 °C and based on WRF model temperatures.

differences also occur between the maps, with the mean growing season temperature and the GFV temperature summation (Figures 6a and c) picking out the warming effect of the sea along a narrow strip near the coastline, while the Huglin index (Figure 6b) indicates greater accumulated heat in the central part of the Wairau Valley.

2. Integration of WRF with the GFV model: 50 % flowering/véraison dates

The GFV model has the following parameters (daily degree-day accumulations) that can be used for prediction of flowering and véraison for Sauvignon blanc: F* = 1282 (50 % flowering); 2528 (50 % véraison), where F* is the critical temperature sum (threshold = 0 °C, starting on the Northern Hemisphere 60th day of the year - 29 August in the Southern Hemisphere). The WRF model output can be used with the GFV model to map the timing of flowering and véraison across vineyard regions, as shown for Marlborough in Figure 7.

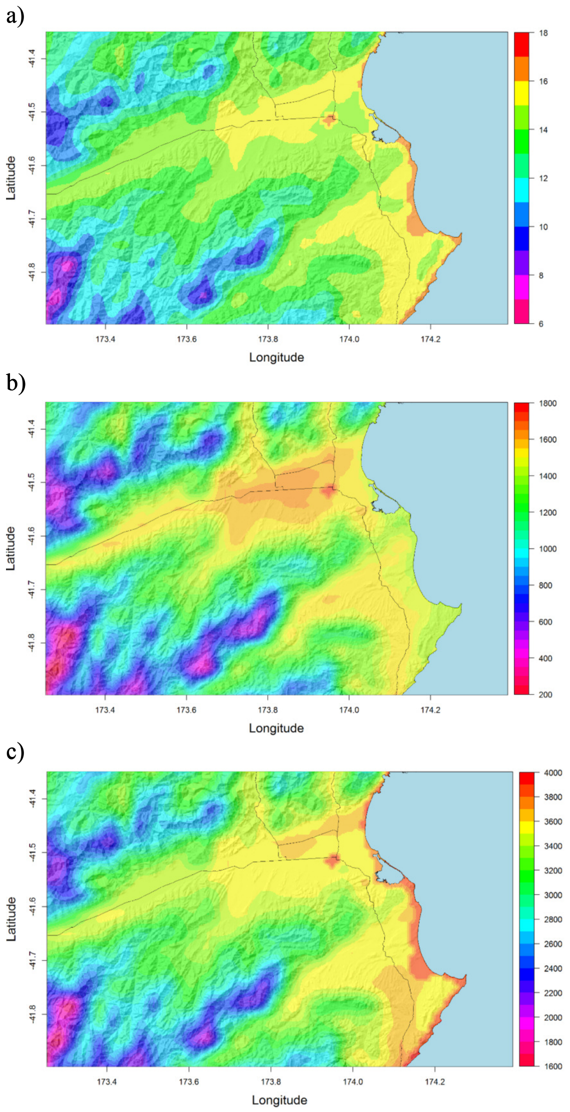

Figure 6 - Maps of: a) mean growing season temperature, b) Huglin index, and c) GFV temperature summation, based on the 2008-9 to 2013-14 growing seasons in the Marlborough region.

Figures 7a and b illustrate the extent of inter-seasonal variability in the development of flowering across the region. Using a combination of WRF model output and the GFV model, the development of key phenological phases can be mapped across a region of complex terrain like Marlborough, to provide the basis for predicting the magnitude and timing of harvest for different parts of the region.

3. Optimal mean growing season temperatures for key Marlborough grape varieties

The WRF-predicted spatial variation in mean growing season temperature (GST) can also be mapped and compared with published optimal ranges of values

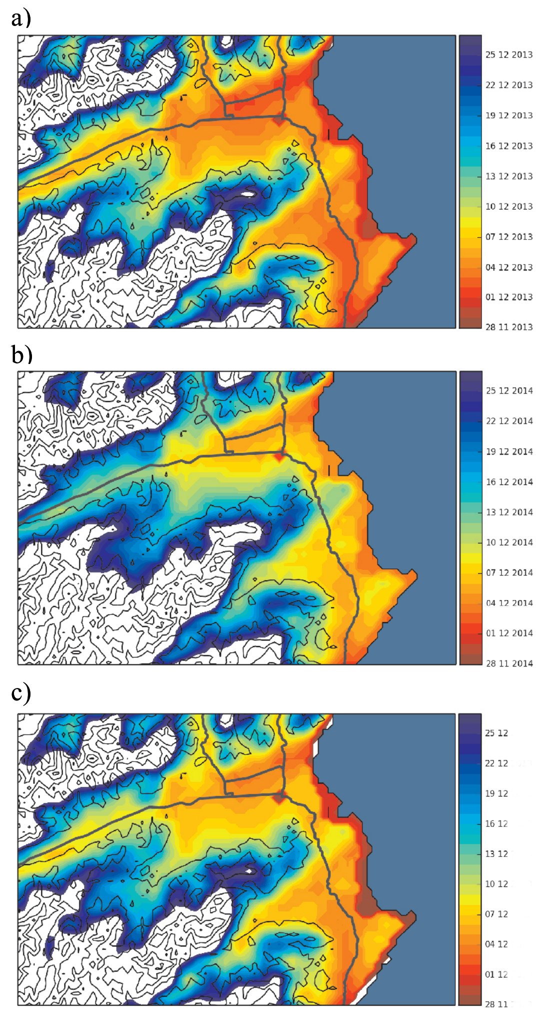

Figure 7 - Isochrone maps of 50 % flowering over the Marlborough region during the growing seasons of: a) 2013-14, b) 2014-15, and c) 2008-14. The key in c) indicates the average day and month of the year.

associated with different grape varieties (Jones, 2006 and 2007):

- Pinot gris [13 – 15.2 °C],
- Chardonnay [14.2 – 17.2 °C],
- Pinot noir [14 – 16.2 °C],
- Sauvignon blanc [14.8 – 18 °C].

(approximate values extracted from graphs in Jones, 2006 and 2007)

In Figure 8, the different mean growing season temperature ranges considered optimal for the four most important Marlborough grape varieties are plotted using the same colour scale, so that the red colours at either end of the scale indicate marginal regions, while the blues and greens represent the most optimal areas for each grape variety.

Based on the WRF-derived temperatures and published optimal temperature ranges for grape varieties, the most optimal grape variety for the Marlborough region appears to be Pinot noir, rather than Sauvignon blanc, which is by far the dominant variety in the region. There are three possible reasons for this anomalous result. First, the cold bias of the WRF model tends to suggest that both Sauvignon blanc and Chardonnay are less optimal than they really are, while Pinot noir and Pinot gris appear to be more optimal.

Second, the ranges of GST used to represent optimal growing conditions for the different grape varieties are based on typical values of GST obtained from regions where those varieties are currently successfully grown (Jones, 2006 and 2007). This rather assumes that the present-day thermal environment is the main reason for the grapes being located where they are, when in fact historical and cultural factors may also be important.

Third, Marlborough, and in particular the Awatere Valley, produces a grassy style Sauvignon blanc. The grapes are harvested at a lower level of ripeness (at a higher 3-isobutyl-2-methoxy-pyrazine content) than in other parts of the world where Sauvignon blanc is produced, and this creates a distinctive wine style.

Conclusions

The application of mesoscale weather/climate models to vineyard regions such as Marlborough (in New Zealand) provides improved knowledge of the unique features of the weather/climate (sea breezes, foehn winds, mountain/valley winds, cold air ponding, etc.) and their contribution to the local 'terroir'. Models such as WRF can also be used to investigate the relationship between weather/climate and key phases of grapevine development at vineyard scale within wine-producing regions. Variability of climate can be investigated across vineyard regions at high resolution using such models, allowing

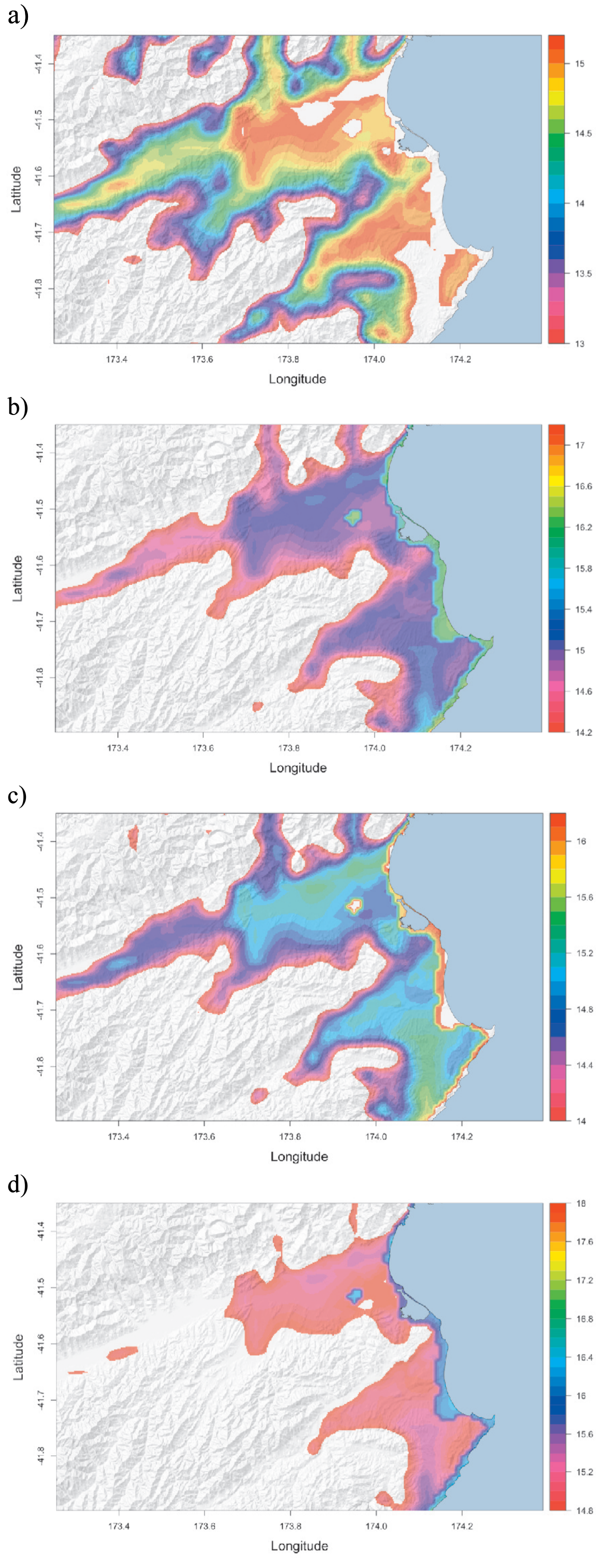

Figure 8 - Maps of optimal mean GST ranges for the main Marlborough grape varieties: a) Pinot gris, b) Chardonnay, c) Pinot noir and d) Sauvignon blanc, based on WRF model output for 2008-2014.

identification of optimal/marginal areas for winegrape production and climate risk assessment based on various bioclimatic indices. Such analysis can also be used to assess the robustness of vineyard regions to longer term climate change, including how much change would be required to make a region unsustainable with respect to specific grape varieties.

The use of the WRF model to assess the suitability of specific grape varieties in the Marlborough region suggests that we need to investigate the origin and nature of the cold bias in model predictions in order to provide more accurate simulations of near-surface temperatures and hence bioclimatic indices. It is also important to improve understanding of the relationship between climate parameters such as average growing season temperature and grapevine response to be able to better assess the future of quality wine production in specific areas in response to changing climate. It is therefore important that future work addresses the limitations identified in combining WRF modelled temperatures with bioclimatic indices by coupling WRF with phenophase models at a higher temporal and spatial resolution.

The suitability of grape varieties to specific areas also depends on the style of wine. For example, Marlborough Sauvignon blanc is generally harvested at a commercial soluble solids (SS) of 20.5 to 21.5 °Brix. Other regions and styles may require a higher SS and therefore take longer to achieve that target. It may therefore be more logical to base suitability of grape varieties on the temperature summation it takes to reach a particular SS target (based on the GFV model).

The effects of manipulation of the grapevine environment at vineyard scale should also be integrated into more comprehensive modelling systems, as the effects of variations in the regional climate could be offset by vineyard management techniques (Webb *et al.*, 2012).

In conclusion, it should be noted that Global Climate Models (GCMs) provide only a general idea of the larger-scale changes in climate likely to occur in vineyard regions over future decades (as discussed by Hannah *et al.*, 2012 and 2013, and van Leeuwen *et al.*, 2013). It is evident that downscaling GCM output to the regional and local scales is fraught with difficulty in regions of complex terrain as the interaction of hemispheric and synoptic scale processes with local and regional topography can introduce significant spatial variation in response to large scale forcing (Sturman and Quénol, 2013). It is therefore important that methods of dynamical and statistical downscaling be improved to allow more realistic assessment of the impacts of climate change on vineyard regions, in order to develop appropriate and effective adaptation strategies.

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Climatic variability in Saint-Emilion, Pomerol and surrounding appellations

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Abstract

Abstract: Soil and climate are major factors involved in terroir expression. In many winegrowing regions, soils have been mapped at very fine scale and new technologies like electric tomography allow to asses variations in soils even at the intra-block scale. In comparison, few studies address local climatic variability and its impact on vine development and grape ripening. Recent technological development, including miniaturization of temperature sensors and shelters, utilization of Digital Elevation Models (DEMs) and Geographic Information Systems (GISs), allows mapping of air temperatures (a major climatic parameter) across winegrowing areas at a very fine scale.
In this paper, the winegrowing region of Saint-Emilion, Pomerol and their satellite appellations is presented (covering 12,200 ha of vineyards). 90 miniaturized temperature sensors have been installed in vineyard blocks across this area in December 2011. Daily temperature recordings over the period 2012-2014 were used in combination with environmental co-variables, mostly linked to topography, to create spatial models of temperature distribution over the area at a daily time step.
The output of this research is a series of very precise maps of minimum and maximum temperatures, as well as bioclimatic indexes (Huglin and Winkler index). Maximum temperatures are lower and minimum temperatures are higher on plateaus located at higher elevation. Higher maximum and lower minimum temperatures were recorded in the valleys. Temperature sums computed as Huglin index show a clear west (warmer) – east (cooler) gradient. Phenology and grape ripening were monitored over the area and the effect of spatial temperature variability on vine phenology and grape ripeness is discussed. Growers actually adapt their plant material and viticultural techniques to temperature variability in the area. This knowledge can be used to adapt viticulture to climate change over the next decades.

Keywords: Saint-Émilion, Pomerol, viticulture, temperature, scale, model, phenology

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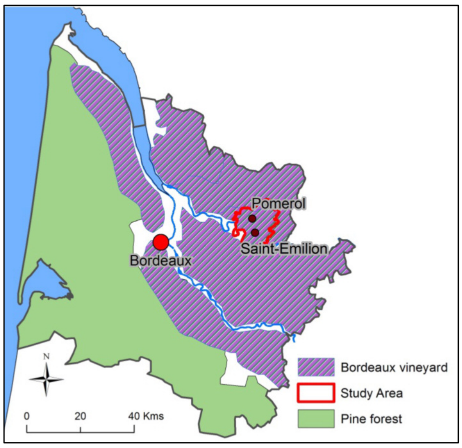

Figure 1. Bordeaux vineyard and the area of Saint-Emilion and Pomerol

Introduction

1. General presentation

The Saint-Emilion and Pomerol appellations are located in the north eastern part of the Bordeaux area, on the right bank of the Dordogne River, close to the city of Libourne (Figure 1), 40 km from Bordeaux.

This area principally produces red wine, including some of Bordeaux' most prestigious estates, such as château Cheval Blanc, Pétrus and château Ausone. Most estates are small in size and many are still family owned. Saint-Emilion became famous at the end of the XIXth century, when Merlot became a major variety in Bordeaux (much later compared to Médoc and Sauternes). The reputation of Pomerol was established only in the XXth century with the help of influential négociants which were established in the city of Libourne in the 1930's.

The main varieties grown in the Saint-Emilion and Pomerol area are Merlot (approximately 70%), Cabernet franc (approximately 25%) and Cabernet-Sauvignon (approximately 5%). Major appellations are Saint-Emilion and Saint-Emilion Grand Cru (5350 ha under vines), Pomerol (750 ha), Lalande de Pomerol (1150 ha), Montagne Saint-Emilion (1600 ha), Saint-Georges Saint-Emilion (190 ha), Puisseguin Saint-Emilion (725 ha) and Lussac-Saint-Emilion (1440 ha). Most vineyards are planted at densities between 5,000 and 6,000 vines per hectare. Vines are guyot pruned and training system is vertical shoot positioning. For vineyard floor management, cover crop is widely used in particular in hillside vineyards to prevent erosion. Tillage is also a common practice and the use of herbicides is declining.

2. Landscape

The Dordogne valley contains many traces of prehistoric civilization, the best known being the Lascaux cave paintings, and menhirs are present around Saint-Emilion. The town of Saint-Emilion was named after the monk Emilion, who was on his way to Santiago de Compostela but never made it. Viticulture was introduced in this part of Aquitaine by the Romans, and later developed around many monasteries and hospices. The status of 'jurisdiction' of Saint-Emilion was granted during English occupation in the XIIth century. Since then, wine has been largely appreciated by both clergymen and non-clergymen. Viticulture has developed as the main agricultural activity and has continued to develop towards the exceptional landscape we know today, which was designated as a World Heritage Cultural Landscape by the UNESCO in 1999. Many prehistoric and historic monuments, ancient villages, vineyards and exceptional wines attract tourist from all over the world to get a taste of this unique terroir.

3. Geology and geomorphology

The vineyards of Saint-Emilion and Pomerol are located on geologic sediments which were established during the Tertiary and Quaternary era.

This area is characterized by several large tertiary limestone plateaus at approximately 100 meters in altitude, shaped by the erosion of the rivers which flow south (Dordogne) and north-west (Isle) of the study site. On the flat valley floors, gravelly and sandy soils have developed on quaternary alluvium (van Leeuwen *et al.*, 2014). The soil map of Saint-Emilion (Figure 2) shows the major soil types present in this area (Robinson, 2006).

4. Climate

Climate is oceanic and temperate. Total yearly rainfall is 785 mm, and mean annual temperature is 13.7°C (Figure 3). Rainfall is well distributed throughout the year, although slightly lower in the summer.

Materials and methods

1. Spatial temperature variability

Given the importance of temperature on vine development and wine quality, it has become of major importance to improve our assessment of this parameter for a better adaptation of plant material and training systems to local climatic variability in a context of climate change.

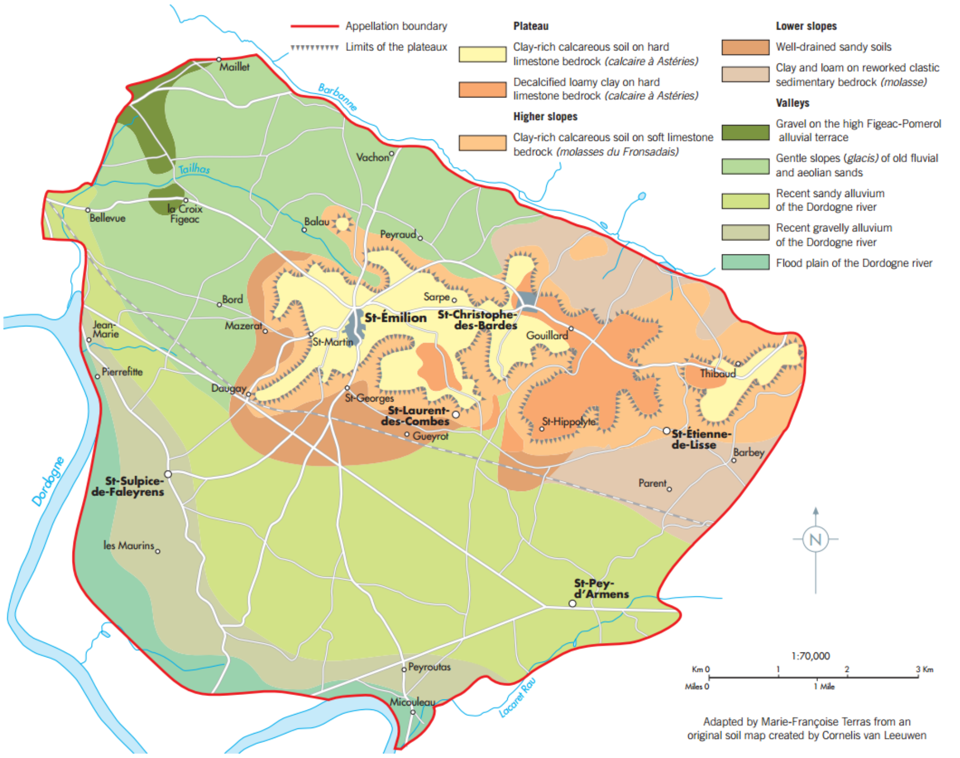

Figure 2. Soil map of the Saint-Emilion appellation (Robinson, 2006)

In order to characterize temperature variability in this area of 19 233 ha (12,200 ha of vineyards), a network of 90 temperature sensors was set up in 2012. This represents a density of 1 sensor for 210 ha.

The temperature sensors used in this project are Tinytag Talk 2 (Gemini Data Loggers, UK). These sensors can be easily installed on vine posts in vineyard plots. The data loggers have been parameterized in order to record both minimum and maximum hourly temperatures.

At this local scale, it is important to take into account not only topography (exposition, slope, altitude), latitude and longitude, but also local parameters, such as rivers, urban areas and soil types, which can have an influence on the spatial distribution of temperature (Figure 4). Topographic data are provided by a Digital Elevation Model (DEM) at a grid of 25m (Institut Géographique National, IGN).

The diversity of this area, both in terms of topography, local parameters and soil types, is particularly suitable for studying fine-scale temperature variations.

2. Aims of this research project

Fine-scale maps of microclimate variability in this area were produced based on the combined use of data provided by temperature sensors and spatial models integrating environmental co-variables implemented at a daily time step. The effect of temperature on vine development and wine quality was assessed by monitoring phenological stages and grape ripening dynamics.

Improved prediction of the consequences of climate change on vine development and grape ripening at a very local scale will allow a better adaptation of viticultural practices and plant material to changing conditions.

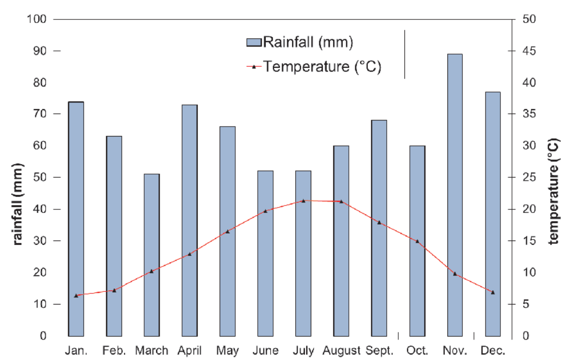

Figure 3. Monthly temperature and rainfall in Saint-Emilion. Average 1994 - 2015, station château Cheval Blanc (data: Météo France).

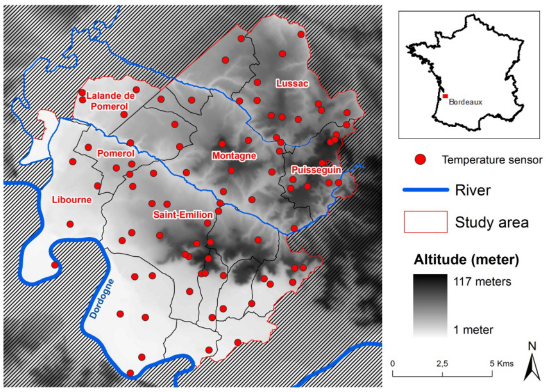

Figure 4. Localization of temperature sensors projected on a Digital Elevation Model (IGN)

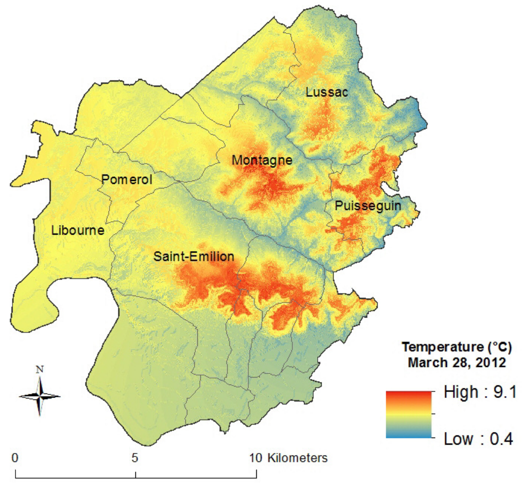

Figure 6. Minimum temperatures of March 28th, 2012

Results

1. Temperature is highly variable, in particular for minimum temperatures

It is of particular interest to look at the daily amplitude of minimum and maximum temperatures over the study area (i.e. the difference between the sensors recording the highest and the lowest minimum temperature over the study area on a particular day; idem for maximum temperature). In 2012, the amplitude of maximum day temperature was mostly around 3 °C, while amplitude of minimum day temperature was about 4°C (Figure 5). The latter fluctuates up to a maximum of 10°C on specific days with anticyclonic clear sky conditions. The map of the minimum temperatures of March 28th (Figure 6) represents a day with 9°C amplitude on minimum temperature. Relief plays an important role in this spatial distribution. Temperatures were lowest in the valleys, due to cold air drainage, and highest on the limestone plateaus.

The analysis of atmospheric circulation patterns and local weather types shows that northwesterly/northerly circulation pattern combined with clear local weather type days promotes high spatial temperature ranges, while southerly circulation pattern combined with overcast and rainy local weather type days are favorable to low spatial temperature ranges.

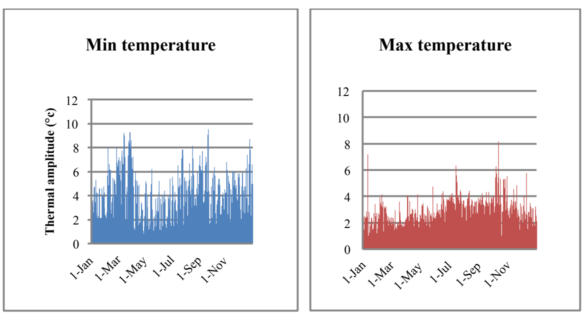

Figure 5. Daily temperature amplitude for minimum and maximum temperatures over the study area

2. Spatial distribution of minimum temperature during the vegetative season

The map of average daily minimum temperatures during the 2012 vegetation period (Figure 7) shows that the highest minimum temperatures are recorded at the highest altitude on the limestone plateaus, in the Pomerol winegrowing region and in the Libourne

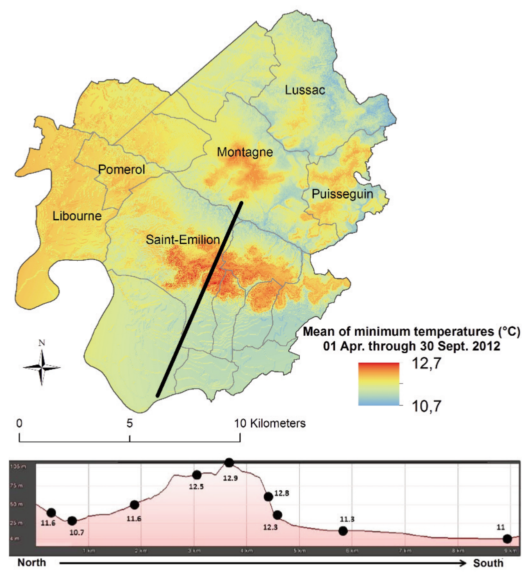

Figure 7. Map of average daily minimum temperatures during the vegetative period for 2012. Cross section through the Saint-Emilion appellation

area in the western part of the study area. The lowest minimum temperatures are recorded in depressions around creeks and in the alluvial plain of the Dordogne River (southern part of the study area). The absolute range of average minimum temperatures recorded over the growing season is 2.5°C. This range was reduced to 2.0°C after spatial modeling.

3. Spatial variability of maximum temperature during the vegetative season

For the distribution of maximum temperature (Figure 8), the opposite spatial pattern is observed: the warmest temperatures are recorded at low altitudes and cool temperatures at high altitudes. Some high maximum temperatures are also recorded in the western part of the area (Pomerol and Lalande de Pomerol appellations and the Libourne area). The absolute range of average maximum temperatures recorded over the growing season is 2.0°C. This range was reduced to 1.3°C after spatial modeling.

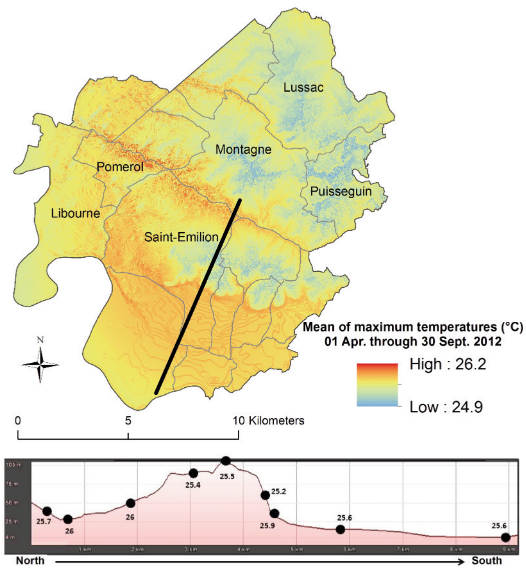

Figure 8. Map of average daily maximum temperatures during the vegetative period for 2012. Cross section through the Saint-Emilion appellation

4. Variation in spatial distribution of Winkler index is strongly linked to relief

The Winkler index is well adapted to study the influence of temperature on vine development. The result shows great amplitude (270°C.days in average) during the years 2012 to 2014 (Table 1). Given this temperature range, vine development could be delayed by 30 days in the latest ripening plots, compared to early ripening plots. We can also see the temporal variations which correspond to the vintage effect. 2014 was warmer than 2012 and 2013.

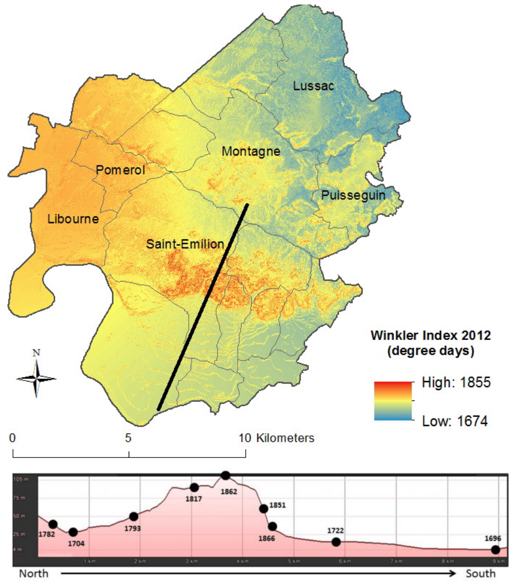

Figure 9. Spatial distribution of Winkler index in 2012. Cross section through the Saint-Emilion appellation

The map of this index in 2012 (Figure 9) shows a spatial structure which is linked to relief and environmental parameters. The limestone plateau of Saint-Emilion and its south facing slopes are the warmest parts of the area. The north-east of the area, the south-east and the bottom of the valleys are cooler. Another warm part of the region, not specifically linked to topography, is the western part of the area around the city of Libourne, including Pomerol.

Statistical analysis using multiple linear regression of all the temperature sensors and environmental parameters confirms that the Winkler index is significantly explained not only by a west-east gradient of temperature but also by altitude and slope.

61% of the variance is explained by a negative west-east gradient effect, 21.5% is explained by altitude and 13.9% by slope in the 60% of the global variance explained by the model.

5. Spatial distribution of Huglin index is related to spatial distribution of maximum temperatures

Another agroclimatic index used in viticulture is the Huglin index. Contrary to the Winkler index, there is

Table 1. Winkler index (2012-14)

	Winkler index		
	2012	2013	2014
Minimum	1622	1617	1704
Maximum	1889	1855	2019
Amplitude	268	238	315

Table 2. Huglin index (2012-14)

	Huglin index		
	2012	2013	2014
Minimum	2195	2096	2231
Maximum	2391	2286	2485
Amplitude	196	190	254

more weight of maximum temperature and it includes a day length coefficient depending on latitude. Like for the Winkler index, there is great spatial variability (200°C.days; Table 2). It is also possible to see the temporal variations which correspond to the vintage effect. 2014 was warmer than 2012 and 2013.

The map of this index in 2012 (Figure 10) shows a spatial structure which is different compared to the spatial distribution of the Winkler index and which is linked to the weight of maximum temperature in this index. The spatial distribution of the Huglin index over the study area shows a strong west-east gradient (Figure 10).

Statistical analysis using multiple linear regression of all the temperature sensors and environmental parameters confirms that the Huglin index is significantly explained by a west-east gradient of temperature and by slope.

64.6% of the variance is explained by a negative west-east gradient effect and 20.2% is explained by

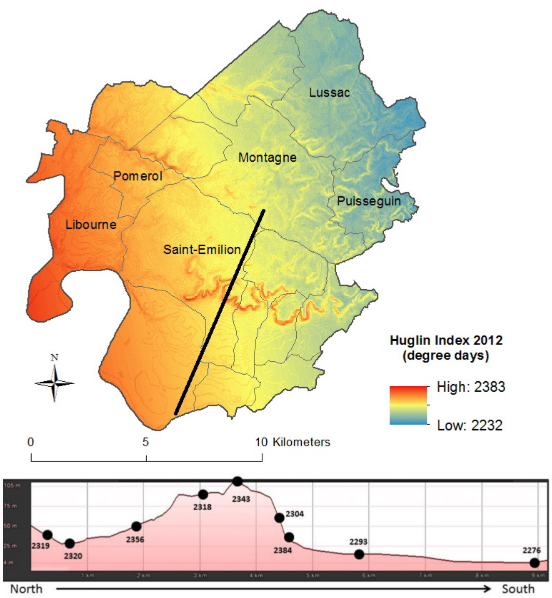

Figure 10. Spatial distribution of Huglin index in 2012. Cross section through the Saint-Emilion appellation

slope in the 25% of the global variance explained by the model.

6. Wide amplitude of mean temperatures, comparable to recent climate change

The average temperature over the study area is slightly above 14°C during the period 2012 to 2014, with an amplitude between the warmest and the coldest temperature sensors of 1.4°C (Table 3).

Analysis of the database of the Bordeaux-Mérignac weather station shows a 1.3°C increase of average annual temperatures from 1951-1980 to 1981-2010 (Table 4).

The range of mean temperature over the Saint-Emilion - Pomerol area is as important as the range of recent global warming.

7. Vine response to climate variability

Phenology was monitored on 18 plots of Merlot from 2012 to 2014 (Table 5). These results show in particular how important the vintage effect was: the warmer climatic conditions of 2012 and 2014 advanced the timing of phenological stages compared to the cool year 2013.

Another point that needs to be highlighted is the intra annual variability. We recorded a window of about 8 days for flowering and 15 days for veraison. The influence in terms of maturity is even more pronounced, with a difference of more than 20 days between the earliest and the latest sugar ripeness (day of the year grape sugar level reaches 200 g/L).

This last point is a key factor to implement adaptation of grapevine varieties and training systems in a context of climate change.

Conclusion

Major spatial temperature variability in the Saint-Emilion - Pomerol winegrowing region has been shown in this study. This can induce differences of up to one week in the timing of flowering, two weeks for veraison and three weeks for sugar ripeness. The range of temperature is only slightly lower than that recorded by Bois (2007) over the whole Bordeaux area. The range is also similar in range to the warming caused by global change over the past century (IPCC, 2007). Growers are producing great wines in this area over the whole temperature range. This means that they have implemented the necessary adaptations to integrate these temperature differences. Growers do also adapt their practices to year to year (vintage) variability. In the frame of this

Table 3. Average temperature (2012 to 2014)

	2012	2013	2014
Mean temperature	13.8	13.7	15
Minimal mean temperature	13.1	13	14.3
Maximal mean temperature	14.6	14.4	15.7
Amplitude	1.5	1.3	1.4

Table 4. Analysis of Bordeaux-Mérignac weather station data from 1951 to 2010

Average mean annual temperature from 1951 to 1980	12.5°C
Average mean annual temperature from 1981 to 2010	13.8°C
Difference	1.3°C

Table 5. Phenology and sugar maturity for Merlot (2012-14)

	Year	Period	Mean date	Spatial variability (days)
Flowering	2012	30/05 - 08/06	4 June	10
	2013	15/06 - 20/06	17 June	6
	2014	31/05 - 07/06	3 June	8
Veraison	2012	31/07 - 18/08	9 Aug	19
	2013	16/08 - 26/08	21 Aug	11
	2014	30/07 - 16/08	7 Aug	18
Sugar maturity (day of the year sugar concentration reaches 200 g/L)	2012	22/08 - 12/09	01-sept	22
	2013	05/09 - 4/10	21-sept	30
	2014	31/08 - 22/09	10-sept	23

study, these adaptations will be studied and will provide insight in potential adaptations to climate change.

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Issues to be considered for strategic adaptation to climate evolution
Is atmospheric evaporative demand changing?

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Abstract

The predicted developments in climate are region-specific and adaptation can only be successful considering the regional characteristics with its diverse technical, environmental, economic and social implications. Beyond some obvious adaptation strategies in response to emerging environmental constraints for example there are many more "basic" challenges below "the surface". One of the key concerns for many regions is the availability of water and how increasing temperature will drive the evaporative demand of the atmosphere. For this, individual regions need to be analysed to quantify possible associated risks. This paper will address differences in regional water relations of grape growing areas in different parts of the world as a basis to address the points listed above.

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Introduction

Climate change effects on the terrestrial water cycle show regional differentiated patterns. While temperature is increasing in many world grape growing regions (Jones *et al.,* 2005; Schultz and Jones, 2010; Webb *et al.,* 2012; Hannah *et al.,* 2013; Tóth and Végvári, 2016) precipitation patterns can vastly differ between regions and can show substantial temporal variations (between and within years) (IPCC, 2014). From rising temperatures it is mostly assumed that water holding capacity of the atmosphere will increase in the future as a function of the Clausius-Clapeyron law (Krysanova *et al.,* 2008) which predicts an increase in the saturation vapour pressure of the atmosphere of 6-7 % per degree Celsius. As a consequence, a simultaneous increase in potential evapotranspiration (the amount of water that could potentially be evaporated from soils and transpired by plants due to changes in climatic factors such as temperature, vapour pressure deficit, radiation and wind speed, ion of water from the soil and transpiration of water from plants, ETp) is assumed in many cases, which would alter soil and plant water relations. However, the same underlying principles also predict an increase in precipitation by 1-2 % per degree warming (Farquhar and Roderick, 2007). Additionally, model predictions for many regions forecast altered precipitation patterns and thus in combination with the possibility of increased ETp, farmers around the world fear an increase in the likelyhood of water deficit and the availability of water for irrigation.

However, the large spatial and temporal variability in precipitation patterns between regions preclude generalizations in predicted consequences with respect to soil and plant water status development. Especially the temporal variability may mask longer-term trends in the development of ETp and consequently soil and plant water status (vVan Leeuwen *et al.,* 2010). Additionally, the focus on the developments within a growing season (spring-summer) in many studies may miss decisive effects occurring during the "off-season" (winter-early spring) but having substantial carry-over effects into the season.

Evaporation is driven by changes in temperature, humidity, solar radiation and wind speed and contrary to expectations due to climatic changes, there have been reports on a reduction in evaporative demand worldwide (Farquhar and Roderick, 2007). In many cases this has been related to a decrease in solar radiation observed for many areas on earth including wine growing regions in Europe until the beginning of the 80th (global dimming, (Wild *et al.,* 2005; Hofmann and Schultz, 2010)) of the last century. However, ETp in some areas has continuously increased which suggests that changes in the aerodynamic component must have more than offset the decrease in radiation over that part of the observed time span (Schultz and Hofmann, 2016). For some regions in Germany, wind speed and vapour pressure deficit (VPD) of the atmosphere have increased in the past and contributed to changes in evapotranspiration (Bormann, 2011) but this is not in agreement with a worldwide observed decrease in wind speed and pan evaporation (Farquhar and Roderick, 2007; McVicar *et al.,* 2012).

These conflicting observations depending on climate classification, country or region, make it necessary to analyze grape growing regions with respect to developments in ETp and precipitation patterns much more in detail in order to make predictions with respect to an increased risk in terms of water shortage. There is a general lack of studies analyzing the past development in ETp and precipitation for different wine growing regions across the planet in order to answer the question whether the threat for sustained drought will increase. When ETp was set to increase in a future climate scenario, substantial reductions in pre-dawn leaf water potential resulted when a dynamic physiological grapevine water model was used (Lebon *et al.*, 2003) to estimate water consumption (Schultz and Lebon, 2005). However, the large spatial and temporal variability in precipitation patterns between regions preclude generalizations in predicted consequences with respect to soil and plant water status development.

Water limited worlds versus energy limited worlds

Those parts of the earth where evaporative demand exceeds supply (rainfall), like many Mediterranean-type climatic regions, are very different from those parts of the world where rainfall exceeds evaporative demand, like for example Germany or many French grape growing areas. In the latter areas there is drainage to aquifers and runoff and to rivers, and evaporation rate largely depends on the available energy and especially the radiation received. In water-limited regions, there is an excess of energy (e.g. solar radiation), and the actual evaporation rate can be close to the rainfall (Farquhar and Roderick, 2007). Grape growers from these different parts of the world have a very different view on their environment. The distinction between water limited versus energy limited worlds is not completely consistent because winters for example in water limited areas will, in a lot of many cases, be part of the energy limited "world" in Fig. 1 based on Budyko (1974) and a conceptual analysis of Farquhar and Roderick (2007). Following this analysis, the actual evaporation rate, Ea, must be less than or equal to evaporative demand, ETp, and also less than or equal to precipitation, P (Fig. 1). The water-limited regions or the water limited part of the season (which could be part of both general areas) are on the left, and the energy-limited regions (or parts of the season) are on the right of the figure.

Material and Methods

The base of possible changes in ETp is a change in temperature which has been observed in many regions. One of the largest collections of climate data (temperature, rainfall, sunshine hours but no data on ETp) from grape growing regions has been published in Gladstones (1992) based on observations for different time periods depending on the source and the availability of data. Four of these data sets from different regions in the northern and southern hemisphere with a strong reputation for growing Cabernet Sauvignon (Bordeaux, Napa Valley, Coonawarra and the Barossa Valley) were extracted from Gladstones (1992) and compared to data from the same stations (or at least very close) for the last 25 years since 1990 (end of observational period in Gladstones book) to get a feeling ofinvestigate the magnitude of changes in temperature which has occurred over that time span. Figure 2 shows the differences in average monthly temperature for the growing season months.

It is obvious from Figure 2 that in all regions shown, temperature has increased albeit to a different extend, which in principle would satisfy the Clausius-Clapeyron relationship which predicts an increase in the saturation vapour pressure of the atmosphere of 6-7 % per degree Celsius, thus increase ETp if air moisture would not change.

In order to evaluate different grape growing regions with respect to observed changes on precipitation patterns and ETp and in order to validate or disproof general observations on changes across the planet (Farquhar and Roderick, 2007), the data of five wine-growing areas in four countries in the Northern and Southern hemisphere across a large climatic trans-sect were analyzed. Climatic data for this analysis were provided by the German Weather Service (Deutscher Wetterdienst) for the location Geisenheim in Germany (50,0° N, 8° E) in a temperate climate, the French INRA CLIMATIK, Agroclim project for the locations Dijon, Burgundy (47,2° N, 5,2° E), temperate climate, and Avignon (43,9° N, 4,9° E) in a Mediterranean climate, the US California data provision system on integrated pest management for Oakville, Napa Valley, CA (38,3° N, 122,3° W), a Mediterranean climate situation, and the Australian Government, Australian Bureau of Meteorology, for

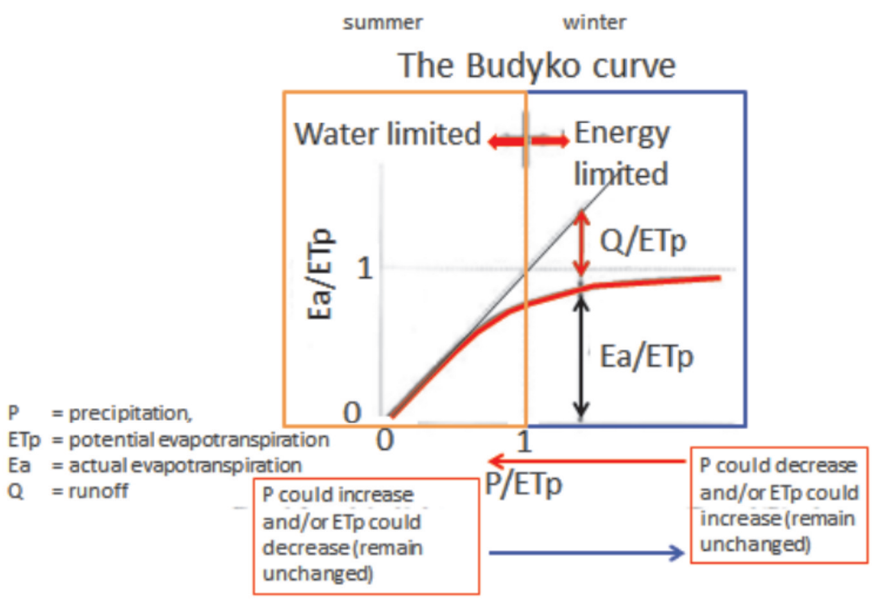

Figure 1 - Inter-relationship between average precipitation (P), actual (Ea) and potential (ETp) evapo-transpiration and runoff (Q) and how season and climate change could affect this inter-relationship depending on the region. Grape growing areas are represented in both water and energy limited areas and the effect of climate change might be substantially different for different parts of the world. The original curve is known as the Budyko curve (Budyko 1974) and the presented figure is an adaptation from Farquhar and Roderick (2007) in an extended version.

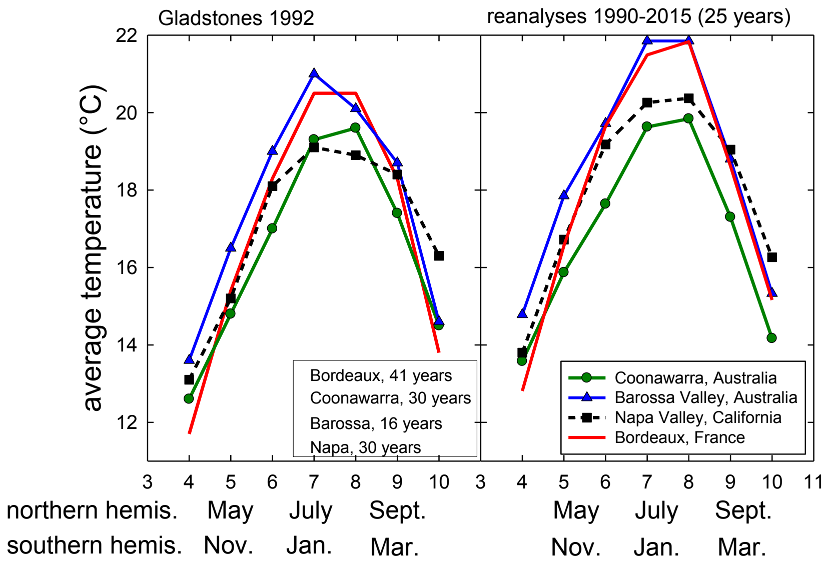

Figure 2 - Average monthly temperatures for four different grape-growing regions with a reputation to grow Cabernet- Sauvignon.

Left panel; data extracted from Gladstones book (1992), right panel; data from the same stations where possible or for stations close by for the last 25 years (1991-2015). Data sources were Météo Bordeaux, US California data provision system and the Australian Bureau of Meteorology.

Williamstown, Adelaide hills (34,7° S, 138,9° E). Data were seasonally separated into precipitation and ETp "summer" for the growing season (May-October for the northern hemisphere, October-May for the southern hemisphere), which in agro-meteorological terms is defined as the "hydrological summer" (Bormann, 2011), and the "off-season" (November-April for the northern hemisphere, April-November for the southern hemisphere), the "hydrological winter". In the case of the German data, predictions for precipitation rates and ETp were used based on model-outputs of a regionalized version of the STARII model of the Potsdam Institute of Climate Impact (Orlowski *et al.*, 2008). STARII constructs time series from 2007-2060 by resampling of observed weather data according to trend informations of the Global climate model ECHAM5/OM (A1B) (Jacob, 2005). This approach provides physical consistency of the combination of the weather variables and is in close agreement compared to the statistics of observed climatology (Orlowski *et al.*, 2008).

Results and discussion

The general expectation, which is also very prevalent in the popular press, that as the world warms because of increased greenhouse forcing there will be a widespread increase in evaporative demand has been challenged by data proving the contrary and by a lack of scientific basis put forward by several scientists (see discussion by Farquhar and Roderick, 2007). Peterson *et al.* (1995) were the first to publish the results from 190 sites in the former Soviet Union, where they found decreasing pan evaporation rates in the European sector, a decline in Siberia, and no trend in the Asian part. Since then many other reports from different parts of the world have been published but none has explicitly looked at grape-growing regions.

Observed and predicted summer trends for areas in Europe and California

Figure 3A shows observed (calculated according to Penman-Monteith) and predicted changes in ETp during the growing season (May-October) for the temperate wine-growing region of the Rheingau (Geisenheim, Germany, 50.0° North, 8° East) from 1958 until 2060 (Schultz and Hofmann, 2016). To smooth out temporal variability, 10-year running mean values were used. There is a clear increase in the difference between ETp and precipitation rate during the growing season already observed during the past 55 years and this development will continue in the future as predicted using a regionalized version of the STARII model (Orlowsky *et al.*, 2008) (Fig. 3A). A similar increase in ETp was also observed for the Mediterranean region near Avignon, France, since the mid-seventies of the last century, but with no observed change for about the last 20 years (Fig. 3B). Available data for the Napa Valley in California show that ETp has not changed for approximately 30 years despite concomitant observations on rising temperatures.

Obvious from Figure 3A are the cyclic patterns of both ETp and precipitation rates, both for the period of observation and the projections until 2060. These cycles may be related to solar cycles which have been made partly responsible for the warming during the first half of the last century but not during the second half (Stott *et al.*, 2003). However, there is some uncertainty on whether these cycles do continue to have an impact on the temporal development of warming on earth and consequently on evaporation (Stott *et al.*, 2003) but the data do show that variability and the development of extremes will become more likely despite cyclic variations (Fig. 3A) (IPCC, 2014). These cycles have an important effect on how climate change is perceived by humans since they can somewhat mask long-term trends (when precipitation is increasing or ETp is decreasing for several years) or on the contrary suggest a speed-up in these trends (Fig. 3A).

Precipitation trends in Avignon have undergone some fluctuations but there was no distinct decrease observed, similar to summer precipitation in the Napa Valley, albeit on a much lower level (Fig. 3B). If ETp predictions for the cool climate area of Germany (50° North) would be correct, then summer ETp values by the middle of the current century would be similar to Avignon (43,9° North) in the seventies at lower precipitation rates.

Observed trends for Australian and California regions (summer and winter)

Analyzing data from one Australian region, Williamstown in the Adelaide Hills, it is obvious that neither ETp nor precipitation have changed substantially over the time period of available data confirming other data from Australian sites (Roderick and Farquhar, 2004) (Fig. 4). The long-term data set from Williamstown shows that ETp decreased between the seventies and the nineties during both winter and summer before increasing again to the early ETp values. This might have been related to the phenomenon of global dimming, a reduction in solar radiation observed in many areas during that particular period caused by increased cloudiness and aerosols (Wild *et al.*, 2005; Hofmann and Schultz, 2010). Precipitation rates also show no clear trend with a slight decrease during winter for the Adelaide Hills (left panel, Fig. 4). Similarly, ETp during winter and summer of the Napa Valley location did not change appreciably (Fig. 4), yet winter precipitation has almost been halved over the

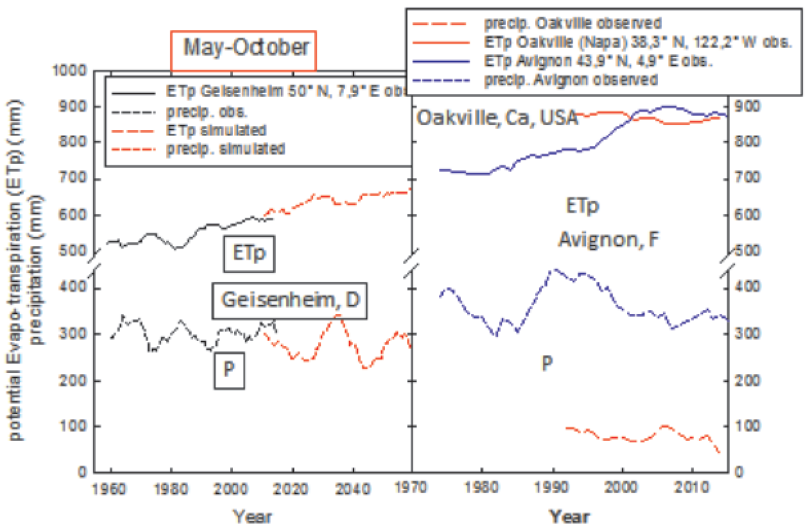

Figure 3 - Observed and simulated precipitation and potential Evapotranspiration for the hydrological summer (May-October) for Geisenheim in the Rheingau region (Germany, 50° North; 8° East) (left panel).
Potential Evapotranspiration rates for the observed time period (1958-2013) were calculated according to Penman-Monteith. Simulations were conducted with the STARII model of the Potsdam Institute of Climate Impact using the medium realization run (Orlowski *et al.* 2008) (adapted from Schultz and Hofmann 2016). In the right panel, observed ETp and precipitation data are shown for two Mediterranean type climate locations, one in Avignon, France, the other at Oakville in the Napa Valley, California. Data show 10-year running mean values. Observed data were from the Deutsche Wetterdienst, Germany, the French INRA CLIMATIK, Agroclim database and the US California data provision system on integrated pest management at the University of California, Davis.

past 25 years, moving the area from an energy limited towards a water limited part on the Budyko curve (Fig. 1). Despite of a “natural” focus on the developments within the growing season, changes in the water budget during the “off-season” seem to become more important (Fig. 4 left panel). Regardless of the fact that during winter and spring precipitation rates are exceeding ETp, the “gap” between these two factors determining the soil water balance is decreasing in some areas (IPCC, 2014). This suggests that for this particular region winter precipitation will eventually be matched by winter ETp with important consequences for the amount of water stored in the soils at the beginning of the growing season. It may also have consequences for the use of cover crops during the winter.

The phenomenon that ETp remains stable or decreases in many regions even in the post-global dimming period has been related to different combinations of effects, yet the most pronounced effect seems that the wind speed in many areas has decreased (Farquhar and Roderick, 2007). A recent paper on the situation in China showed that wind speed has declined by 25-30 % since the nineties (Liu *et al.,* 2014) and a decrease of similar magnitude has been observed for the Cape region in South Africa (Hoffmann *et al.,* 2011) and are implicated in the worldwide decrease in evaporative demand (McVicar *et al.,* 2012). Data on wind speed are not easily available, but over the same time period, wind speed has not changed in several German regions (data not shown) and in some even an increase has been observed (Bormann, 2011), which could be part of the explanation of different trends for different areas.

Observed trends for cool climate regions in Germany and France (winter and summer)

Aside of Mediterranean-type, low summer rainfall climates (water limited) with a more or less continuous decline in water availability over most of the growing season, temporary water deficits also commonly occur in temperate, summer rainfall regions, specifically on vineyard sites with shallow soils and low water holding capacity (i.e. vVan Leeuwen *et al.,* 2010). As compared to an irrigated vineyard situation in moderate or even hot climates, the natural cycles of stress and relieve can be much more pronounced albeit completely unpredictable in frequency, duration and severity in these areas and are naturally part of the ‘terroir’ and the year to year variation in wine quality. Most classic European grape growing regions are unirrigated and examples are given for two classical cool climate regions and the observed trends in ETp and precipitation during winter and summer (Fig. 5). Despite being classified as cool climate regions, both precipitation and ETp differ vastly. Geisenheim has higher ETp than Dijon in winter (Fig. 5A) and up to the nineties this was

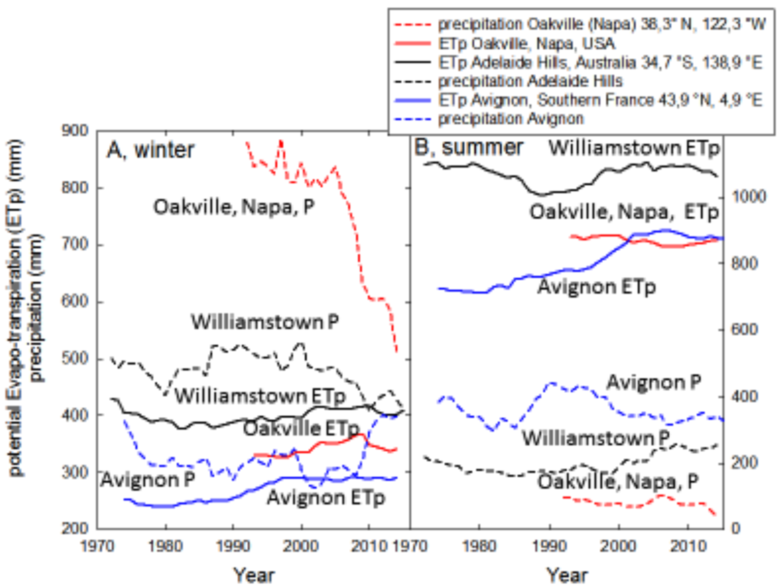

Figure 4 - Observed precipitation and potential Evapotranspiration for the winter (left panel) and summer periods (right panel) for Oakville, Napa Valley, California (USA, 38,3° North, 122,3° West) and Williamstown in the Adelaide Hills (Australia, 34,7° South, 138,9° East).

Avignon data from France have been added to illustrate how different regional situations are in broadly defined “Mediterranean climates”. Data show 10-year running mean values. Observed data were from the US California data provision system on integrated pest management at the University of California, Davis and the Australian Bureau of Meteorology, Australian Government and the French INRA CLIMATIK, Agroclim database.

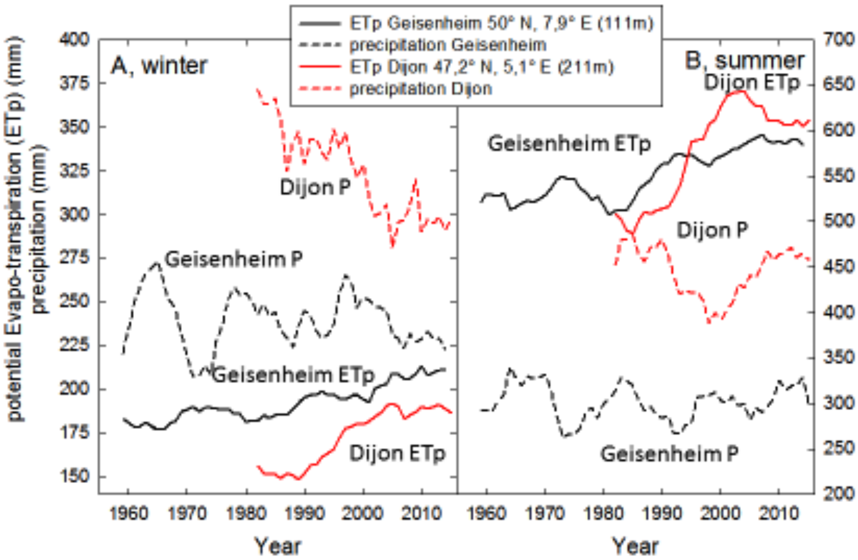

Figure 5 - Observed precipitation and potential Evapotranspiration for the winter (left panel, A) and summer periods (right panel, B) for Geisenheim, Germany (50° North, 8°East) and Dijon, Burgundy, France (47,2° North, 5,1° East). Data show 10-year running mean values.

Observed data were from the Deutscher Wetterdienst, Germany, and the French INRA CLIMATIK, Agroclim database.

also the case for summer (Fig. 5B). Geisenheim shows a continuing increase in ETp over the past 60 years in both winter and summer, whereas Dijon in Burgundy showed a strong increase starting in the nineties for both winter and summer with no change or even a decline over the past 10-15 years during the summer months (Fig. 5B). Precipitation follows a cyclic trend in all regions and in all seasons with a strong decrease in winter precipitation in Dijon over the last 35 years (Fig. 5A). In general Precipitation and ETp are inversely correlated which would be according to theory (Farquhar and Roderick, 2007).

Conclusions

The data show that generalisations with respect to global developments are not possible and that each individual region needs to be analysed with respect to observed trends and also with respect to expected developments (Hofmann *et al.,* 2014). The reasons for different developments in ETp seem to be complex and little understood. Trends might also be influenced by the drawing of moisture from water bodies which could balance the increases in temperature. According to the Budyko hypothesis, change in actual evaporation in dry regions is dominated by change in precipitation rather than potential evaporation. In humid regions, such as the cool climate examples given here, the change in actual evaporation is controlled by change in potential evaporation rather than precipitation, which would mean that the development of water deficit would become more likely in the future. Of all regions analysed, none has shown a continued decrease in ETp or an increase in precipitation as observed for other parts of the world (Farquhar and Roderick, 2007). Rising CO_2-concentration with its effect on stomatal closure and thus potential reduction in water use may also play a role in changes in the balance between precipitation and ETp (Gedney *et al.*, 2006).

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Multi-seasonal effects of warming and elevated CO_2 on the physiology, growth and production of mature, field grown, Shiraz grapevines

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Abstract

Industry concerns in Australia about the impacts of climate change have, to date, focused on the effects of warming, particularly shorter maturation periods. The effects of elevated CO_2 concentration (eCO_2) on C_3 plant physiology have been extensively studied and suggest that eCO_2 impacts on viticulture could affect grapevine shoot growth, fruit production and fruit composition. We previously used open top chambers (OTC) with an active heating system to study the effects of elevated air temperature (eTemp) on mature grapevines in the field. This system was augmented with the ability to elevate atmospheric CO_2 and established in a mature Shiraz vineyard in a factorial combination of eTemp and eCO_2. Three seasons of observations on the eTemp only treatment corroborated our previous study; all aspects of phenology were advanced, but leaf function was largely unaffected. In contrast, the effects of eCO_2 on phenology were small in the first season, but increased over the subsequent two seasons. Interactive effects of the treatments on gas exchange were observed; photosynthesis rates were significantly higher in the eCO_2+eTemp treatment, compared to eCO_2 alone, suggesting that the likely future climate will have a larger impact on viticulture than might be predicted from experiments examining only one of these factors.

Keywords: Shiraz, temperature, CO_2, phenology, leaf function

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Introduction

There is now a large body of literature suggesting that the emission of CO_2, and other gases of anthropogenic origin, is resulting in warming of the troposphere (summarised in IPCC 2014). This combination of higher CO_2 concentrations and warming of the atmosphere is of particular importance to viticulture, due to the longevity of plantings and a limited ability to change varieties or relocate to cooler areas due, to the cost and difficulty of doing so.

To date, industry focus has been on the potential effect of warming on vine phenology (e.g. Petrie and Sadras 2008, Webb *et al.*, 2012) and our previous work with open top chambers in the field has demonstrated that 2°C of atmospheric warming is indeed enough to cause a significant advancement of all major phenological stages (Sommer *et al.*, 2012).

However, the largest contributory factor to climate warming is CO_2 and atmospheric CO_2 concentrations are rising year on year at a rate that has been shown to affect photosynthetic rates in C_3 plants, relative to pre-industrial times, (Gerhart and Ward, 2010) and is expected to have an even larger effect in the future.

To date, no viticulture experiment has been able to address the combined effects of elevated atmospheric CO_2 (eCO_2) and elevated atmospheric temperature (eTemp) in the field. We have established an open top chamber (OTC) facility in a major Australian winegrape growing region using mature Shiraz vines, managed to current industry best practice, which is able to impose an eCO_2 treatment of 650 ppm and an eTemp treatment of +2°C relative to ambient, simulating the likely climate around 2075. The facility applies these treatments in a factorial design and is thus able to separate effects of eCO_2 and eTemp as well as be used to study their interaction. The facility was fully operational prior to the 2013/14 southern hemisphere growing season and has been running continuously since that time.

Materials and methods

The experiment was established in a block of mature Shiraz grapevines at the Department of Economic Development, Jobs, Transport and Resources (DEDJTR), Irymple, Australia,. Sixteen open top chambers (OTCs), 5.4x4.8x2.4 m (LxWxH), were erected, each enclosing a single panel of three vines. The OTC structure, heating system and fan-only system are described in Sommer *et al.* (2012). The CO_2 enrichment system (described in Edwards *et al.*, 2016) was designed to allow CO_2 to quickly mix with

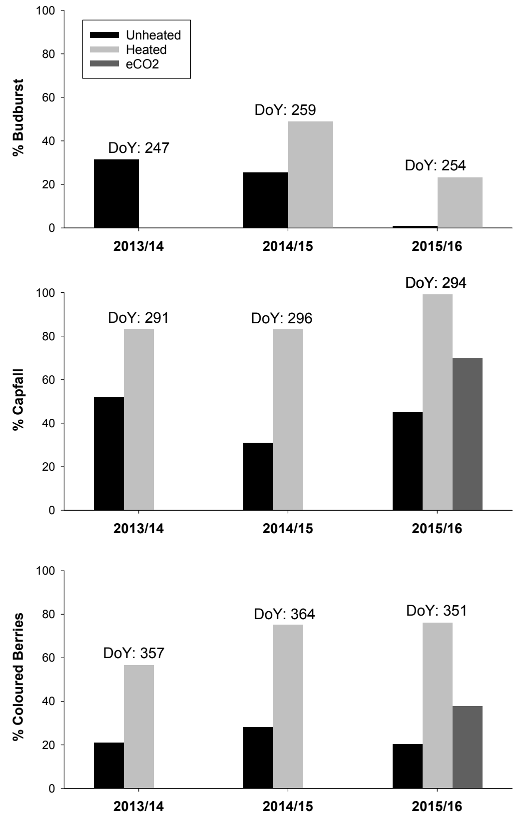

Figure 1 - Proportion of buds burst (a), capfall (b) and coloured berries (c) at a time point chosen to demonstrate the effect of 2 °C of warming (light grey) and elevated CO_2 (dark grey), compared to controls (black), in each of three growing seasons of treatment (only significant effects shown)

the chamber air and be transported in and around the grapevine canopy by air movement (with or without the heating system fan running). CO_2 was only supplied during daylight hours, with timing adjusted weekly. As grapevines are a deciduous woody perennial plant, requiring chilling for even budburst (Mullins *et al.*, 1992), the temperature treatments were maintained over each winter.

Four chambers were assigned to each of the treatment combinations: elevated temperature (eTemp), elevated CO_2 (eCO_2), elevated temperature and elevated CO_2 (eCO_2 +eTemp). The remaining four chambers were assigned as controls (chamber control) and were provided with a fan-only system to replicate the air movement generated by the heating system, without providing heating. Finally, a further four panels of vines were assigned to be non-chambered controls (chamberless control). The OTCs and chamberless control panels were distributed in a randomised design. The trial therefore consisted of 20 plots, with four replicates per treatment.

Air temperature and relative humidity were logged at 15 minute intervals in each of the 20 plots using a HOBO Micro Station Datalogger (One Temp Pty Ltd, Adelaide, SA, Australia), CO_2 concentration measured 5 times per second in each of the OTCs provided with eCO_2, and every second in the control chambers, using Li-Cor (Lincoln, NB, USA) and PP Systems (Amesbury, MA, USA) CO_2 sensors, respectively.

Treatments were applied immediately prior to budburst in the 2013/14 season, and maintained from that point onwards, including during winter. The data presented here represent three seasons of treatment; namely the 2013/14, 2014/15 and 2015/16 southern hemisphere growing seasons.

Vine water use was monitored at 15 minute intervals from September 2013 to June 2015 using a single SFM sap flow logging system (ICT International, Armidale, NSW) in the central vine of all 20 replicates, providing two full growing seasons of data.

The phenological stage of each replicate was determined at regular intervals according to the modified E-L system (data not shown). In addition, weekly photographs were taken and used to establish the onset of key phenological stages.

Leaf gas exchange was measured on four occasions per season on dates roughly equivalent to anthesis, canopy closure and veraison, with a final measurement after harvest. Each measurement was made on a single fully expanded sun-exposed leaf per replicate and consisted of a determination of assimilation under saturating light (A_{sat}) at the chamber/atmospheric CO_2 concentration over the course of one minute, following an equilibration period. The leaves used to measure photosynthesis were harvested at the end of the day, with leaf fresh weight, leaf area and leaf dry weight determined. For the 2013/14 and 2014/15 seasons, the dried leaves were then ground and used to determine the concentration of non-structural carbohydrates (NSC) according to Edwards *et al.*, (2011).

Harvest of all the bunches from the central vine was undertaken once sampling on the adjacent vines indicated that the juice had reached a total soluble sugar (TSS) level of 24°Brix. The total fruit weight was measured and a sub-sample of 100 berries used to determine TSS.

Results and discussion

The experimental system was effective in providing 2 °C of warming above ambient and in raising the CO_2 concentration of the air in the OTCs to an average of 650 ppm (data not shown, but see Edwards *et al.*, 2016). Both values are predicted to occur around 2060-2070 (IPCC, 2014).

Comparison of the environmental results from the control OTCs and the chamberless control plots indicated a small impact of the chamber infrastructure, for example an average air temperature increase close to 0.5 °C. There were also small differences between the control OTCs and chamberless controls in other measured parameters,

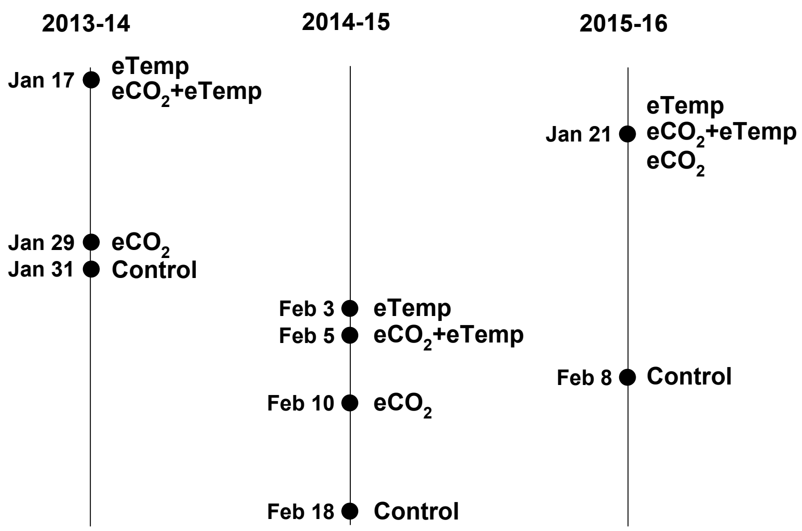

Figure 2 - Timeline of harvest dates for the four OTC treatments for three growing seasons. Harvest dates were based on a target TSS of 24 °Brix.

such as leaf gas exchange (data not shown), but these were not consistent. Consequently, we have presented the non-heated, ambient CO_2 OTC chambers as 'controls' in the following figures and discussion.

1. Phenology and harvest

As the experimental system was only begun a few days prior to budburst in 2013 it was not expected that any effect of the treatments would be observed on the timing of budburst in that season and this was indeed the case (Figure 1a). However, by anthesis in that same season (approximately 45 days later) the two heated treatments reached 50 % capfall earlier than the non-heated treatments (Figure 1b). This advancement of phenology continued and veraison was also advanced in the two warming treatments, with the 50 % coloured berries stage reached ahead of the non-heated treatments, approximately 110 days after budburst (Figure 1c). No significant effect of eCO_2 nor interaction between warming and eCO_2 treatments was observed on phenology during the 2013/14 growing season. The effect of warming in advancing phenology was maintained during the two subsequent seasons of treatment, with the addition that from spring 2014 budburst was also advanced (Figure 1). Again, no significant effect of eCO_2 was observed during the 2014/15 season, but anthesis and veraison were both advanced by the eCO_2 treatment, relative to controls, in the 2015/16 season (Figure 1), suggesting that the direct effects of eCO_2 on phenology may increase over time. However, phenology of vines exposed to the combined eCO_2+eTemp was not advanced relative to the eTemp treatment.

Harvest date was determined by attainment of 24°Brix and was advanced by at least two weeks in the eTemp treatments in all growing seasons (Figure 2). This represented a shorter maturation period, despite the advancement in veraison that was also observed in these treatments. The eTemp and eCO_2+eTemp treatments only separated in one season (2014/15) and only by two days. However, the eCO_2 treatment had an increasing effect with each season; two days advancement in the first season, eight days in the second and 18 days in the third. As with the phenology results, the effect of eCO_2 on the rate of TSS accumulation, represented by harvest date, indicated that the effect of increasing atmospheric CO_2 concentration was increasing with the duration of the eCO_2 treatment.

Fruit yield of control vines varied from 12.8 kg vine^{-1} in 2014 to 18 kg vine^{-1} in 2015. The lower figure may have been due, at least partly, to a heat wave prior to harvest that appeared to have the greatest impact on the eTemp treatment; resulting in a yield of only 9.7 kg vine^{-1}. There were no significant effects of warming on yield in either 2015 or 2016. There was also no significant effect of eCO_2 in 2014 or 2016, but both the eCO_2 and eCO2+eTemp treatments had a greater yield in 2015; 16.9 and 17.4 kg vine^{-1}, respectively. Bindi *et al.*, (2001) reported increased fruit dry mass per m^2 of ground area from grapevines grown under 550 ppm and 700 ppm of CO_2 in two consecutive seasons, albeit from vines with a very different management system than in use here.

2. Leaf physiology

Whilst the warming treatment had the potential to directly impact any enzymatic processes, the major

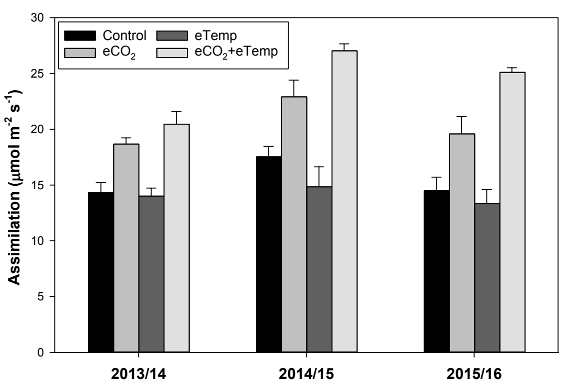

Figure 3 - Assimilation under saturating light of leaves from vines grown under control conditions (black bars), 2 °C of warming (dark grey and pale grey bars) and elevated CO_2 (grey and pale grey bars).

Data are means of field reps ±SE (n=4), averaged across three (2014/15) or four (2013/14 & 2015/16) timepoints.

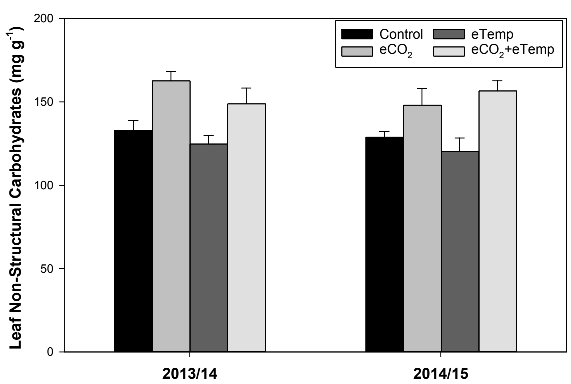

Figure 4 - Non-structural carbohydrate concentration of leaves from vines grown under control conditions (black bars), 2 °C of warming (dark grey and pale grey bars) and elevated CO_2 (grey and pale grey bars).

Data are means of field reps ±SE (n=4), averaged across four timepoints effect of elevated CO_2 on C_3 plants is to increase photosynthetic rates (Campbell *et al.*, 1990), affecting carbohydrate availability and thus other processes limited or regulated by that availability. Measurements of photosynthesis (as A_{sat}), made throughout the three seasons demonstrated this; A_{sat} was 30-40% higher in the eCO_2 treatments than the treatments with ambient air CO_2 concentrations (Figure 3), approximately 390 ppm of CO_2.

There was no reduction in the CO_2 effect during the season (data not shown) or between seasons. In all three seasons, the eTemp treatment had A_{sat} rates that were not different to controls, but the eCO_2+eTemp treatment had significantly higher photosynthetic rates than eCO_2 alone (Figure 3).

This interaction between eCO_2 and warming on maximum photosynthetic rates has the potential for a significant impact in the long-term, due to its potential effect on carbohydrate availability, and demonstrates the ongoing need for experimental work that examines the interaction between these two climate variables in the field.

The influence of the treatments on carbohydrate availability was examined by analyzing the NSC in leaves, specifically the same leaves on which photosynthetic rates were measured. The 2015/16 season data was not available at the time of writing, but the data from the two previous seasons demonstrated a significant effect of the eCO_2 treatments, with a 15- 20% increase in NSC, relative to ambient CO_2 treatments (Figure 4). There was no clear effect of the warming treatments, even the thougheCO$_2$+eTemp treatment that had higher photosynthetic rates. However, respiration rates, which could be expected to have been influenced by warming as leaf temperatures were higher (data not shown), and NSC export were not measured and differences in these processes could explain differences between treatment effects on A_{sat} and on NSC.

Stomatal conductance of C_3 plants grown under eCO_2 is commonly lower than plants grown under current atmospheric CO_2 concentrations (Ainsworth and Rogers 2007). This was observed in all three seasons for the eCO_2 treatment, relative to control (Figure 5). In contrast, the eTemp treatment did not significantly alter stomatal conductance, corroborating the observations in our previous work (Sommer *et al.*, 2012). The eCO_2+eTemp treatment also did not significantly affect conductance, relative to controls. The intercellular CO_2 concentration of the eCO_2+eTemp treatment was not different to the eCO_2 treatment, suggesting that the higher photosynthetic rates of this treatment, compared with eCO_2 alone, may be driving a higher stomatal conductance due to the impact of those rates on intercellular CO_2 concentrations (Mott 1988).

Transpiration rates, reflecting stomatal conductance, were lower for vines in the eCO_2 treatment compared to the controls (Figure 6). In contrast, vines in the eCO_2 +eTemp treatment had higher rates, but only in 2015/16, which also happened to be the season with the highest absolute rates, probably due to the warmer weather conditions in that season. Whole season water use, measured by sapflow, exhibited similar treatment effects to the leaf level transpiration rate in the control, eCO_2 and eCO_2 +eTemp treatments (Figure 7), but was highest in the eTemp treatment despite the lack of an effect on leaf level transpiration rates. This may have been due to the retention of leaves on vines longer compared to the controls (visual observation only, no formal assessment made), higher rates of transpiration outside the midday period where leaf level measurements were made, e.g. early/late in the day or at night, or a less obvious factor.

Conclusions

Warming had an impact on vine phenology from shortly after the treatment was applied onwards, advancing phenology significantly at all major stages. In contrast, eCO_2 only started to affect phenology in the third season after treatments began. To date, there has been no evidence of an additive effect of the two treatments, with phenology of the eCO_2 +eTemp matching that of the eTemp treatment. Although warming alone had little effect on leaf physiology, there was a strong interaction between

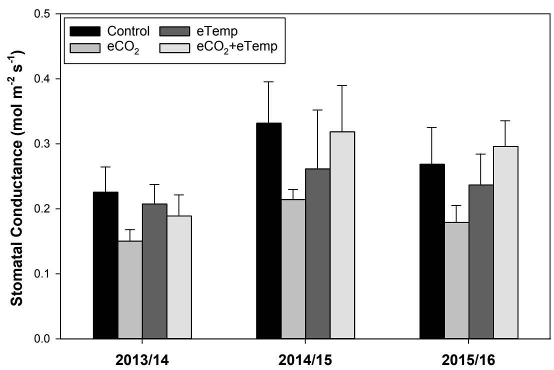

Figure 5. Stomatal conductance of leaves from vines grown under control conditions (black bars), 2°C of warming (dark grey and pale grey bars) and elevated CO2 (grey and pale grey bars).

Data are means of field reps ±SE(n=4), averaged across three (2014/15) or four (2013/14 & 2015/16) timepoints.

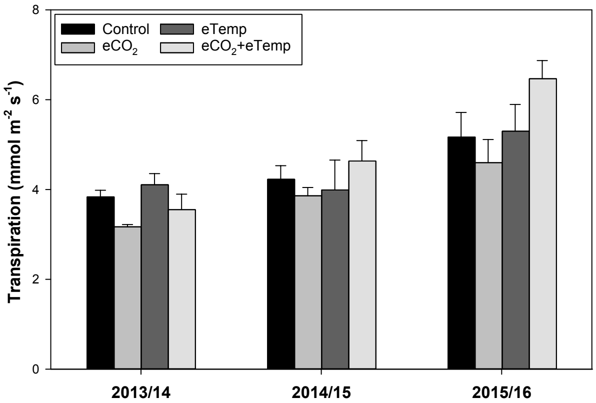

Figure 6. Transpiration of leaves from vines grown under control condi-tions (black bars), 2°C of warming (dark grey and pale grey bars) and elevated CO_2 (grey and pale grey bars). Data are means of field reps ±SE (n=4), averaged across three (2014/15) or four (2013/14 & 2015/16)

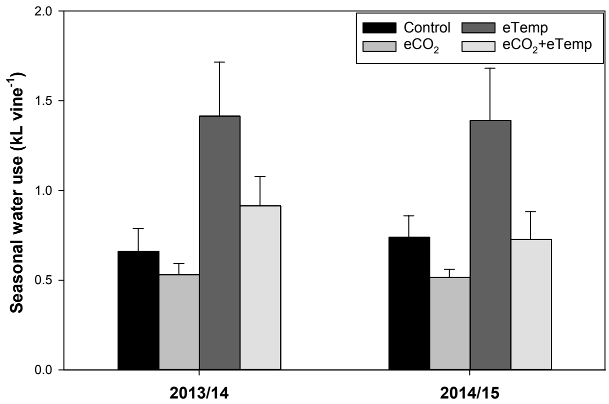

Figure 7. Whole of season water transpired of vines grown under control conditions (black bars), 2°C of warming (dark grey and pale grey bars) and elevated CO2 (grey and pale grey bars). Data are means ± SE (n=4).

elevated CO_2 and warming, with higher rates of photosynthesis when the two were combined than for eCO_2 alone. This suggest that field experiments using only eCO_2 , without a concomitant warming treatment, may underestimate the effects of climate change on viticulture.

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Grapevine phenology in France: from past observations to future evolutions in the context of climate change

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Abstract

Aim: Phenology is a key factor in explaining the distribution and diversity of current vineyards in France. This work has the objective to summarize the different studies developed in France to analyze grapevine phenology.

Methods and results: Several topics are presented: a general description of all historical databases and observatory networks developed in France during the last 70 years; an overview of the different models developed to calculate the main phenological stages; an analysis of the main results obtained using these models in the context of studies of climate change impacts on viticulture in France; and finally a general discussion about the main strategies to adapt the phenological cycle to future climate conditions.

Conclusion: This review emphasizes that even if phenology is not the only trait to be considered for adapting grapevine to climate change, it plays a major role in the distribution of the current variety x vineyard associations.

Significance and impact of the study: It is therefore critical to continue to study phenology in order to better understand its physiological and genetic basis and to define the best strategies to adapt to future climatic conditions.

Keywords: *Vitis vinifera* L., phenology, climate change, dataset, model, observation, France, cultivar

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Table 1. Classification of the phenological timing of the 43 cultivars covering 95 % of the French vineyards.
Five groups of phenological timing were defined using F* values ([1120 - 1411] and [2286 - 2941] for flowering and veraison, respectively) calculated using the GFV model (Parker *et al.*, 2013). Note there are no French vineyard varieties in the Very Early or Very Late classes based on the data published in Parker *et al.* (2013).
Groups were built assuming a normal distribution of the F* value and calculating different percentage values.

		Flowering			Veraison		
Phenology class	**% F* range**	**Range of F* values (based on GFV model in Parker et al., 2013)**	**Number of varieties**	**Varieties**	**Range of F* values (based on GFV model in Parker *et al.*, 2013)**	**Number of varieties**	**Varieties**
Very Early	**< 5%**	< 1134	1	Meunier	< 2318	0	-
Early	**5 - 25%**	1134 - 1192	1	Pinot gris	2318 - 2449	1	Meunier
Medium	**25 - 75%**	1192 - 1338	36	Alicante Bouschet, Aligoté, Aramon, Auwerrois, Cabernet franc, Cabernet-Sauvignon, Carignan, Chardonnay, Chenin, Cinsaut, Clairette, Colombard, Cot, Gamay, Gewurstraminer, Grenache, Grenache blanc, Grenache gris, Grolleau, Gros Manseng, Macabeu, Marselan, Mauzac, Melon, Merlot, Muscat à petits grains, Nielluccio, Pinot noir, Piquepoul blanc, Riesling, Roussanne, Sauvignon, Semillon, Syrah, Vermentino, Viognier	2449 - 2777	38	Alicante Bouschet, Aligoté, Aramon, Auwerrois, Cabernet franc, Cabernet-Sauvignon, Carignan, Chardonnay, Chenin, Cinsaut, Clairette, Colombard, Cot, Gamay, Gewurstraminer, Grenache, Grenache blanc, Grenache gris, Grolleau, Macabeu, Marselan, Mauzac, Melon, Merlot, Mourvèdre, Muscat à petits grains, Muscat d'Alexandrie, Nielluccio, Pinot noir, Pinot gris, Piquepoul blanc, Riesling, Roussanne, Sauvignon, Semillon, Syrah, Vermentino, Viognier
Late	**75 - 95%**	1338 - 1396	5	Caladoc, Mourvèdre, Muscat d'Alexandrie, Tannat, Ugni Blanc,	2777 - 2908	4	Caladoc, Gros Manseng, Tannat, Ugni blanc
Very Late	**> 95%**	> 1396	0	-	> 2908	0	-

Introduction

Phenology is the study of recurring plant and animal life cycle stages in relation to weather and climate (Schwartz, 2013). As for many other crops, grapevine phenology studies have been largely reported in the literature (see Coombe, 1995 and Jones, 2013 for a review). Usually, winegrowers use this information to 1) choose the variety that is more suitable to their vineyard and 2) adapt their practices (i. e. fertilization, topping) to variations in climatic conditions in space (among vineyards) and in time (among vintages).

Phenology is considered as the first biological indicator of climate change (Menzel *et al.*, 2006). In the past, the three main grapevine phenological stages (budbreak, flowering, veraison) and the harvest dates have been used to quantify the magnitude of climate change in several vineyards over the world (Jones *et al.*, 2005). In this context, phenology is also described as one of the main factors to be explored for varietal adaptation (Duchêne *et al.*, 2010).

Grapevine diversity is large, representing 5000 – 10000 cultivars of *Vitis vinifera* L. (Lacombe *et al.*, 2013). Phenological diversity of this species is particularly high and has been addressed in several studies quantifying and describing the existing variability for this trait at the species level (Boursiquot *et al.*, 1995, Parker *et al.*, 2013).

Currently in France it is possible to cultivate 347 varieties for fruit production (wine grape and table grape). However, only 10 varieties (Merlot, Grenache, Ugni blanc, Syrah, Cabernet-Sauvignon, Chardonnay, Carignan, Cabernet franc, Pinot noir and Sauvignon) represent 71.7 % of the total surface area of planted vines (FranceAgriMer, 2014), and only 43 varieties cover 95 % of the total vineyard surface area in France (800.000 ha). In accordance with the classification provided by Parker *et al.* (2013), most of these 43 varieties can be classified in the medium category class in terms of timing of flowering and veraison (Table 1). “Very early” and “very late” phenology classes are underrepresented or not represented at all. This rapid analysis shows that the current available biodiversity for phenology requires further investigation (for example varieties covering the remaining 5 % of the total surface).

The objective of this research summary is to review the different studies developed in France to analyze grapevine phenology. The summary is separated in two main sections: 1) an overview of the work achieved to date using historical databases and different models developed to calculate the main phenological stages; and 2) a general discussion of the main strategies investigated to adapt the phenological cycle to future climate conditions.

Historical observations, databases and observatories

In France there is a long tradition of observing grapevine phenology. Several comprehensive phenological databases have been established over the past 35 years as a result of the extensive collection of diverse phenological data from a range of sites and years.

Multiple grapevine observatories have been implemented in different INRA (French national institute of agronomical research) centers in Bordeaux, Angers, Colmar and Montpellier. In each of these sites, several local varieties (for example Chenin in Angers, Gewürztraminer and Riesling in Colmar) as well as varieties imported from other regions of France (for example Cabernet-Sauvignon in Colmar) have been monitored over several years, in some cases since the 1950s. Near Montpellier, the Domaine de Vassal germplasm repository (www6.montpellier.inra.fr/vassal/), which includes more than 2700 cultivars of *Vitis vinifera* L., was set up in the 1950s, and since then, key stages of phenology have been monitored annually for a number of varieties. All these data have been collected and stored by different methods and by different teams in the last 70 years.

In this context, by the early 2000s, several information systems and databases have been developed in France in order to store, structure and centralize phenological data. In 2002, the PHENOCLIM database was created by INRA in order to compile the historical observed data from main varieties of perennial crops studied at INRA and in other technical institutes. The analysis of this database has highlighted the importance of these historical datasets to study past climate evolution (Domergue *et al.*, 2003). In parallel and for the scientific community working on genetics and genomics, the EPHESIS database, for Environment and Phenotype Information System, has been developed. This module of the GNPIS platform (https://urgi.versailles.inra.fr/gnpis/) is dedicated to the integration of experimental trials on genotype by environment studies (Steinbach *et al.*, 2013). Any data pertaining to phenotypic traits, including plant phenology, can be stored and link to genetic data in this database. Currently, data from cultivar repositories of different experimental sites are integrated in this platform. Another system, the VITPHE database, for Vitis Phenotyping, was also developed in Montpellier and Bordeaux to provide a useful resource for the scientific community working on plant phenotyping and genotype × environment interactions in grapevine (http://bioweb.supagro.inra.fr/vitphe/public/). Under the framework of citizen science actions developed in France, the database "Observatoire des Saisons" (http://www.obs-saisons.fr/) has been operating since 2006 to collect phenology data for a wide range of species, including not just cultivated species but also wild and forest species. Finally, since 2016, an interconnection system of phenology databases was developed in the framework of the PERPHECLIM project (w3.avignon.inra.fr/perpheclim/). This system allows the user to access all the databases described above and to obtain a global overview of the existing data for any given species in the database (in the case of this research, for grapevine).

From these databases and observatories, research studies have illustrated changes in the phenology of several grape varieties in the recent decades, particularly in connection with the increase of temperature. A pioneer study of the relationship between phenology and current climate evolution was carried out by Duchêne and Schneider (2005) analyzing the Riesling dataset from Colmar (Figure 1).

In this series, the authors showed that the main phenological stages (mid-budbreak, mid-flowering and mid-veraison) have advanced significantly over the last 50 years. There has been a change in interannual variability depending on the considered phenological stage : for the 1989-2015 period, interannual variability increased for flowering compared with the 1958-1988 period, but for budburst and veraison the interannual variability decreased for the 1989-2015 period (compared with 1958-1988). These changes and trends did not occur only in the Alsace region (see for example the climatic analysis for the Burgundy region in Richard *et al.*, 2014), but have been observed in almost all French vineyards (data not shown) and in many other vineyards in the world (Jones *et al.*, 2005). All these observations combined with flowering data from other fruit species (i. e. apple blooming data shown by Legave *et al.*, 2013) emphasize the importance of phenological data as an indicator of past climate evolution. This study has also highlighted the necessity of a more comprehensive research to understand the adaptability of crops to climate change.

In the past 15 years, grapevine harvest dates have been used to study past climate evolution. Even if harvest dates cannot be considered as a phenological stage, they have been successfully used as a proxy in past climate studies (Chuine *et al.*, 2004, Menzel, 2005, Meier *et al.*, 2007, Etien *et al.*, 2008, 2009, Yiou *et al.*, 2012, Cook and Wolkovich, 2016). A database was published by Daux *et al.* (2012) with approximately 350 datasets totaling approximately 17000 harvest dates from 22 vineyards covering the 1354-2007 period. The studies based on this dataset have shown that reconstructed temperature anomalies correlated well with other temperature proxies (i. e. tree rings) and the dataset corresponded

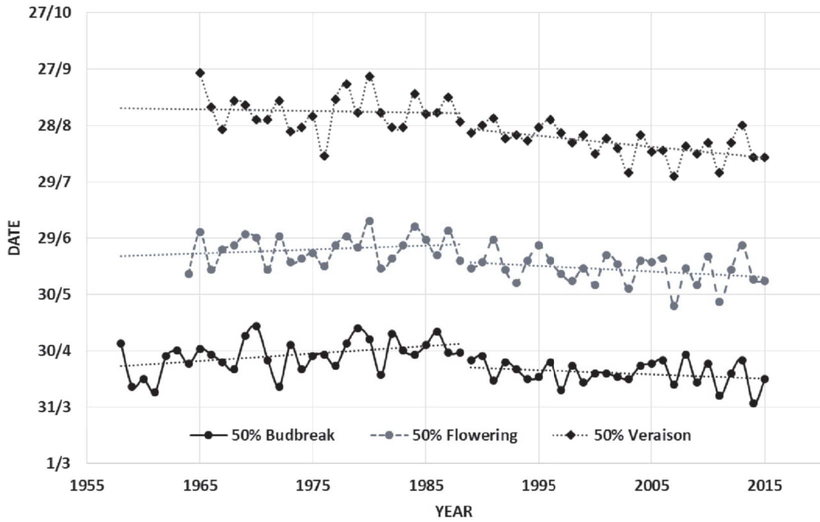

Figure 1. Evolution of the main phenological stages (50 % budbreak, 50 % flowering, 50 % veraison) of the Riesling cultivar in Alsace (Bergheim over the past 60 years.
Data from INRA - Colmar. Trend curves have been added in order to show the breaking point in 1988-1989 as described in the text. The variability is significantly lower in the last 30 years compared with the preceding time period for 50 % budbreak and 50 % veraison stages (9 days vs 6.5 days and 10 days vs 8.2 days, respectively) and slightly higher for 50 % flowering (8 days vs 8.5 days).

to and confirmed the documented temperature anomalies, in particular in long time series (García de Cortázar-Atauri *et al.*, 2010b). Nevertheless, different factors playing a role in the choice of the harvest date (for example variety, wine style, training system, etc.) may have generated more variability in harvest dates over the past four decades. Therefore, it may be important to identify and characterize the uncertainties in climate reconstructions generated by these potentially confounding factors in more recent time series (van Leeuwen and Darriet, 2016).

Faced with the challenges of climate change, new experimental platforms have also emerged in recent years to characterize several traits (including phenology) of grapevines. This is notably the objective of the VITADAPT field experiment at INRA-ISVV in Bordeaux. This experimental system includes 52 *V. vinifera* varieties from different French vineyards and other countries, covering a very large range of precocity. The objective of the VITADAPT project is to characterize this group of varieties and study their suitability to the changing climatic conditions of the Bordeaux area (Figure 2).

Finally, with the objective to breed new grapevine varieties better adapted to future climatic conditions, many teams are studying the genetic basis of phenology (Grzeskowiak *et al.*, 2013, Fechter *et al.*, 2014). For example, Duchêne *et al.* (2012) have characterized the genetic variability created in the progeny of a cross between Riesling and Gewürztraminer (Figure 3). Their results showed that some regions in the grapevine genome are linked to the observed variation in phenology. These regions encompass specific genes that could participate to the genetic variability of grapevine phenology.

The current infrastructures, observatories, information systems, databases and scientific projects have led to the development of a global framework that can be used in future studies to investigate the impacts of climate change on phenology and to define future adaptation strategies.

Phenological process-based models

Phenology modeling has been widely developed for many different species in the last 50 years (Chuine *et al.*, 2013). In this context, several phenological process-based models have been proposed to study grapevine phenology in France. This has been mainly the result of the availability of the large databases described in the previous section. These studies have explored a set of very different issues, ranging from the modeling of some main processes of plant

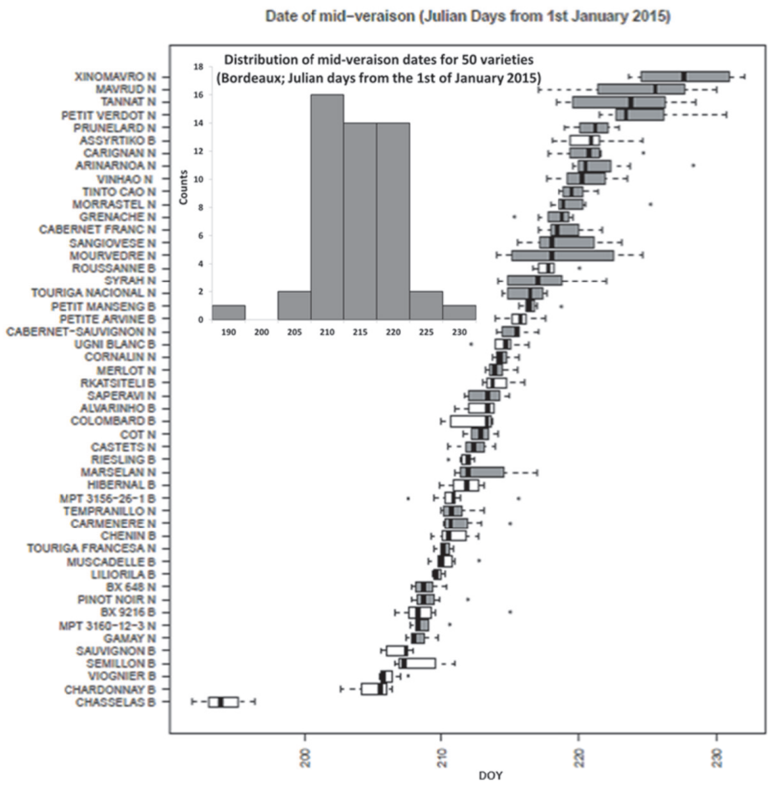

Figure 2. An example of variability among cultivars observed in the VITADAPT experiment (50 % veraison in the vintage 2015). DOY : Day Of the Year.

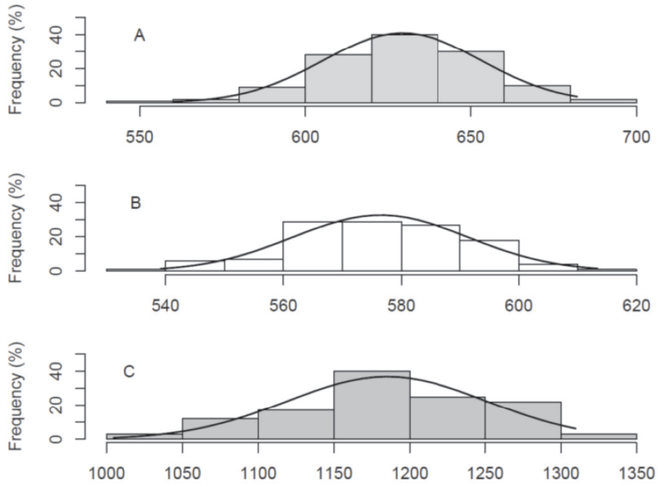

Figure 3. Histogram of segregations of the genotypic effects (heat sums in degree.days of maximum temperatures in 2008) in the Riesling x Gewürztraminer progeny. A) From 15 February to budbreak (base 2 °C); B) From budbreak to flowering (base 10 °C); C) From flowering to veraison (base 6 °C).

development (dormancy break and budbreak) to the classification of varieties for technical purposes, and most recently, the assessment of the impact of climate change on phenology of different varieties in various French vineyards.

Historically, investigations on the dormancy process of grapevines started in the 1960s with the work of Pouget. This author proposed a model to simulate budbreak for various varieties (Pouget, 1988) which was amended by Riou (1994). This model starts calculating the post-dormant phase after January 1st based on the assumption that the grapevine has already broken dormancy by that date (see Lavee and May, 1997 for a review). García de Cortázar-Atauri *et al.* (2009a) subsequently compared Pouget's amended model to the BRIN model, which takes into account the dormancy phase. The BRIN model was built using two different models: the Bidabe's model that was developed to simulate apple flowering (Bidabe, 1965a, b) and the Richardson model that was used to simulate peach flowering (Richardson *et al.*, 1974). The objective of this two-phase model was to determine if problems of dormancy could delay budbreak in some vineyards under future climate conditions, an issue that cannot be assessed with single-phase models.

Other main stages (flowering and veraison) have been simulated using the traditional model proposed by Amerine and Winkler (1944): the linear Growing Degree Days model (GDD) using daily mean temperatures, a base temperature of 10 °C and calculation starting on April 1st. This model has been widely used in the literature, and especially by García de Cortázar-Atauri (2006) to simulate the impacts of climate change on grapevine using the STICS crop model. Subsequently, other models have been calibrated and tested successfully: the linear model proposed by Duchêne *et al.* (2010) using daily maximum temperatures as an input variable and different base temperatures according to the phases simulated; and the curvilinear model of Wang and Engel (1998) adapted by García de Cortázar-Atauri *et al.* (2010a) to simulate grapevine flowering and veraison for several varieties. While the Duchêne model is quite similar to the Winkler model, the Wang and Engel model incorporates several improvements to simulate phenology: the model identifies an optimal temperature for the species (values between 25-30 °C) and makes it possible to define a critical threshold temperature (in this case 40 °C) above which plant development stops completely.

Since 2008, Parker *et al.* (2011, 2013) have undertaken several studies in order to classify the largest number of grapevine varieties using a simple and robust model adapted at the species level (*Vitis vinifera* L.). The authors presented the GFV model (Grapevine Flowering and Veraison model), which is based on a linear function of the mean daily temperature using a base temperature of 0 °C and starting its calculation on March 1st. The model was calibrated from an important database containing more than 4000 observations for flowering and veraison for more than 100 varieties and from different sites, mostly in France, and a few sites in other countries (Switzerland and Italy). This model has been successfully tested in the VITADAPT field experiment for the 2012-2015 period. The average absolute mean error for all the varieties (sum of mean error values by variety/number of varieties) was respectively 3.4 days for flowering and 4.4 days for veraison. This model is being tested also in other countries (i. e. New Zealand and Chile) with similar outcomes (Parker *et al.*, 2015b).

These models can be used to assess phenology evolution under different climate conditions (in space and time). Several studies have been conducted in recent years by using different models combined with climate change scenarios to quantify future changes in the phenology of different varieties in vineyards in France and abroad (e.g. García de Cortázar-Atauri, 2006, Duchêne *et al.*, 2010, García de Cortázar-Atauri *et al.*, 2010a, Pieri, 2010, Caffarra and Eccel, 2011, Cuccia *et al.*, 2014, Molitor *et al.*, 2014). All these studies showed that all main phenological stages (budbreak, flowering and veraison) will advance in the future, with greater advancements predicted in northern than in southern vineyards. In the CLIMATOR project, the authors calculated that flowering will advance by 8 days and veraison by 10 days for every degree increase in temperature in France (Gate and Brisson, 2010).

More recently in the LACCAVE project (www6.inra.fr/laccave), García de Cortázar-Atauri *et al.* (2016) calculated phenology evolution for three varieties (Chardonnay, Syrah and Cabernet-Sauvignon) across several vineyards in France. Figure 4 represents a synthesis of the results obtained.

These results indicated a change in the phenology (all stages) independently of the variety of approximately 6 to 12 days in 2050 regardless of the scenario and of 15 to 30 days depending on the variety, the scenario and the region in 2100 (Figure 4). For example, veraison could be 33 days earlier in Champagne using the scenario RCP 8.5, which generates the most significant changes. As a consequence of the calculated advances in phenology, the maturity phase is also calculated to advance to the warmest period of the year (July and August), generating important changes in the climatic conditions during grape ripening (Duchêne *et al.*, 2010). Finally, as shown in Figure 4, the time range for each phenological stage is calculated to compress under the different scenarios. The consequence for berry quality at harvest will have to be considered as well as the implications for future breeding programs.

How can phenology be used as a key factor for adaptation?

As described above, phenology is a key factor for the adaptation of species to their environment (Chuine, 2010). In this context, it is also one of the factors that can be studied and modified (if possible) to evaluate

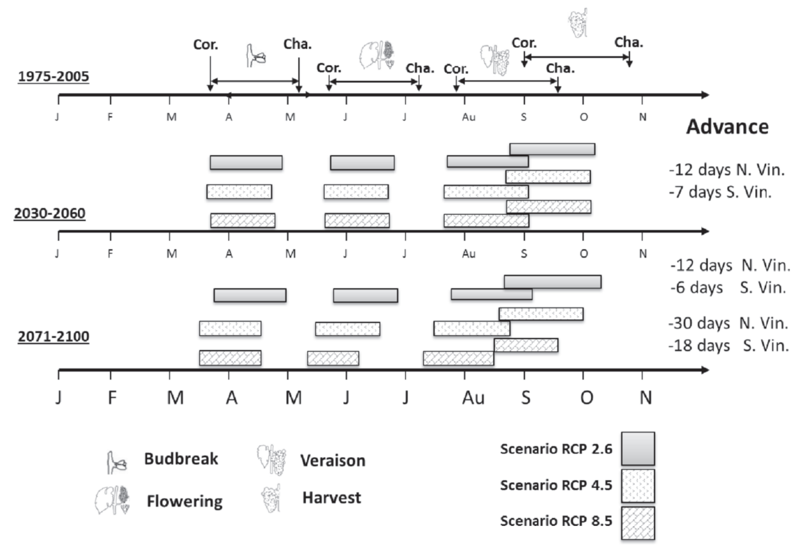

Figure 4. Trends in budbreak, flowering, veraison and harvest (35 days after veraison) in French vineyards calculated for 3 different varieties: Chardonnay (early variety), Syrah (medium variety) and Cabernet-Sauvignon (late variety); using climate data from DRIAS (CNRM-Aladin model - www.drias-climat.fr) for current/past climate conditions (black blocks – period 1975-2005) and three RCP scenarios: 2.6 (grey blocks), 4.5 (grey point blocks), 8.5 (grey brick blocks); for two different periods: 2030-2060 and 2071-2100.

The length of the block represents the period for each phenological event for all the varieties collectively represented combined between the first appearance (50 %) in the first (Cor. = Corse) and the last vineyard (Cha. = Champagne).

N. Vin. represents northern vineyards. S. Vin. represents southern vineyards.

the adaptation capacity of a species/variety to the climatic conditions of a given location.

Unlike wild species (not-cultivated), the presence of a crop, or a variety, in a specific location is the result of a human choice. Historically, based on their experience and analysis of the environmental conditions (i. e. climate), growers have identified what species/varieties are best suited for production in each location. Thus, the best variety x location combinations need to be reconsidered in the context of climate change. One of the main considerations is to delay phenology with two potential options: changing the agricultural practices at the field/vineyard level or changing the variety used.

Recently, the ADVICLIM LIFE program showed that local variability of temperature (at the vineyard level) significantly affected the timing of phenological stages (Neethling *et al.*, 2016). This kind of results and analysis is very important in order to identify new potential areas to produce high quality wines and to define adaptation strategies to face future conditions (see also van Leeuwen and Destrac-Irvine, 2016). In the same way, Verdugo-Vásquez *et al.* (2016) characterized the variability of appearance of phenological stages at the plot level and highlighted the issues of managing these plots using simple models to simulate the phenological timing. This information can be used to better organize field work in order to optimize the choice of treatment dates, harvest date, etc.

At the plot level, several practices have been identified to delay phenology, in particular during the ripening period, in order to escape the summer heat. Very late pruning, after the end of winter and near the budbreak stage, can significantly delay budbreak. This technique is currently applied in northern vineyards in order to escape spring frost damages, but it may be also considered to delay the vegetative cycle of the vine (Branas, 1974, Friend and Trought, 2007). The leaf/fruit ratio has been also identified as a factor that can delay the start of the ripening phase and delay the time to reach a target sugar concentration (Parker *et al.*, 2014, 2015a). Rootstock choice has also been reported as a factor to delay the phenology of grafted varieties, having a significant impact for different stages (budbreak, veraison) of plant development (Tandonnet *et al.*, 2011, Bordenave *et al.*, 2014). Other techniques, not yet systematically used in France, have been developed to modify the timing of main phenological stages and maturity. These include: the use of growth regulators (application of retardants) to delay phenology (Böttcher *et al.*, 2011a, b), or growing grapes under cover, which is usually used for table grapes and other fruit production, and which can advance or delay grapevine phenology according to different production objectives (Novello and De Palma, 2008).

As mentioned before, the other option to modify the phenology in a specific vineyard is based on the choice of the cultivar. In this context, several possibilities exist and are currently being explored in France. One of the simplest, when it is possible, is to change the current proportions of traditional varieties in some vineyards in order to promote late ripening cultivars. For example, in Bordeaux vineyards it may be an option to change the proportion of Merlot in favor of later varieties such as Cabernet-Sauvignon or Petit Verdot, all of which are current traditional varieties of the region. In other cases, particularly in northern vineyards, it may be possible to introduce late varieties that are not well suited so far due to their late maturity. This may also be true for southern vineyards, via the introduction of varieties from warmer and drier climates, for example Agiorgitiko from Greece and Touriga nacional from Portugal. Ancient cultivars abandoned for production, but still existing in the repositories, are currently being tested in some vineyards (for example Barbaroux and Mourvaison in Côteaux de Provence vineyards). In other vineyards where the cultivar choice is limited, as in Burgundy (only Pinot noir, Chardonnay, Aligoté and Gamay can be grown), the phenotypic clonal variability (for phenology and other characters) of the varieties currently grown is being analyzed in order to quantify the adaptive margin. As an example, clone 1209 of the cultivar Chenin has recently been integrated into the French catalog, because it is ripening 5-8 days later than the other Chenin clones (*Barbeau personal communication*).

While we have demonstrated above the importance of phenology, several authors have also shown that it is not possible to adapt to future conditions by taking into account only this parameter. Duchêne *et al.* (2010) showed in Alsace that this strategy was not sufficient to maintain the current climatic conditions during maturation in the future, even using a wide range of cultivars. This work, combined with that published by Parker *et al.* (2013), indicated that despite the numerous cultivars available in repositories, only a few cultivars may be late enough to escape the high temperatures expected to occur during ripening by the end of the century in France. In this context, breeders must also take into account this information and seek to incorporate other traits such as tolerance to high temperatures (heat shock resistance) and/or slower/low sugar accumulation rate in the berry. Nevertheless, the interest of introducing new varieties will strongly depend on the situation in each single vineyard. It will be necessary to assess all the environmental and legal constraints (as for example for the vineyards being under the Protected Designation of Origin - PDO) and the capacity of each vineyard to produce high quality wines responding to consumer demand. In all cases, it is necessary to find a solution adapted to each vineyard, combining several options described above and taking into account the constraints and benefits of each vineyard.

Conclusions

Phenology is a key factor in explaining the distribution and diversity of current vineyards in France. Through studying phenology, the impact of climate change on grapevine has been evaluated over recent decades. The knowledge and information obtained has also been used to assess potential phenology evolution in the future. All these findings have been achieved through the longstanding work of observation, analysis and compilation of this precious information by multiple organizations.

This article has presented a synopsis of research conducted to understand and model the main phenological stages (budbreak, flowering and veraison). However, even if those stages are important to understand the growth cycle of the plant, much remains to be investigated with respect to grape maturity, which is fundamental to determine berry composition at harvest. Some studies have already begun to model the berry maturation process (García de Cortázar-Atauri *et al.*, 2009b, Dai *et al.*, 2016). Nevertheless, it will also be important to produce simplified tools (such as the GFV model) for future analysis of the impact of climate change on this phase which is fundamental to define harvest composition.

Even if phenology is not the only trait to be considered for adapting grapevine to climate change, phenology plays a major role in the distribution of current cultivars. Several strategies have to be implemented in each vineyard to find the best solutions to adapt to future conditions, which may vary greatly depending on the scenario considered. It is therefore critical to continue to study phenology in order to better understand its ecophysiological (e.g. dormancy mechanism) and genetic (fundamental for breeding) attributes. To tackle these issues it is necessary to coordinate efforts on the observation (description of standard protocols, creation of new observatories, development of data management tools, maintenance and enhancement of cultivar and clone collections) via transverse and multidisciplinary programs. Our capacity to adapt to climate change will depend on this multidisciplinary approach.

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Climate vs grapevine pests and diseases worldwide: the first results of a global survey

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Abstract

Aim: This paper aimed to address the relationship between grapevine disease, pest occurrences and climate. The extremely large extension of viticulture worldwide offers the possibility to evaluate the impacts of climate variability on many aspects of the grape growing system. For this, we initiated a global survey to retrieve the most important diseases and pests in many grape growing regions worldwide and to identify the risk of exposure to pests and diseases of viticulture as a function of climate.

Methods and results: Based on the answer of respondent about the main reported diseases/pests in their region, a severity index was calculated. Each region was geolocalised and data were compared to the WorldClim gridded climate database to document the range of climate conditions (growing season temperature and rainfall) associated to the main diseases/pests. The potential climatic-induced changes of grapevine disease and pest geography by 2050 are assessed using agro-climate projections from the ARPEGE CNRM model, using the RCP 4.5 scenario. The preliminary results allow to determine the distribution of diseases as function of agroclimatic indicators.

Conclusion: While the distribution of diseases differs according to the region of the world, the current analysis suggests that mildews remain the major phytosanitary threat in most of the regions. Powdery mildew, trunk diseases and viruses were reported in extremely diverse climatic conditions, including intermediate and wet regions.

Significance and impact of the study: This paper present an original methodology to address the relationship between grapevine disease and pest occurrences and climate. Such documentation is scarce in the current literature. Further analysis is currently being performed, including additional survey answers, climate indices and supplementary data collected (spatial extension, frequency of treatments…) to better depict the challenges of grapevine phytosanitary management in a changing climate.

Keywords: diseases, pests, viticulture, climate change, grapevine

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Introduction

Viticulture sustainability in response to climate change has been addressed mostly considering agronomical impacts such as grape phenology (Xu *et al.*, 2012), grape ripening (Barnuud *et al.*, 2014 ; Stock *et al.*, 2005), and water management (Hofmann *et al.*, 2014), either separately or together (Moriondo *et al.*, 2013 ; Webb *et al.*, 2012). All indicate considerable changes, either recent or projected during the 21st century. The environmental impacts of climate change on viticulture have been explored by Hannah *et al.* (2013). While their conclusion was partially biased (van Leeuwen *et al.*, 2013), their study brought insights into the potential impacts of climate change in the next decades on water use, ecosystems and land use shifts by vineyards. Disease and pest control is another important issue of the environmental footprint of viticulture, potentially leading to pollution (Komárek *et al.*, 2010), human health issues (Ntzani *et al.*, 2013) and economic consequences (Pimentel, 2005). Climate change is likely to affect parasite biology and populations and, therefore, plant protection is expected to evolve in response to the increase and/or decrease of pest or disease development in the vineyard (Caffarra *et al.*, 2012 ; Salinari *et al.*, 2006). Phytopathology responses to climate change have to be addressed by considering (1) changes in plant sensitivity to the pathogen, (2) the response of the parasite, and sometimes its vector, to climate and (3) changes in the parasite ecosystem, taking into account global changes from cultivation, climate and pathogen/pests interactions.

While the biology of grapevine sensitivity to many parasites and pest or disease agents is well documented (Chuche and Thiéry, 2014 ; Esmenjaud *et al.*, 2008 ; Gadoury *et al.*, 2012 ; Gessler *et al.*, 2011 ; Reineke and Thiéry, 2016), the evolution of populations and potential breaking of life cycles in response to climate change is difficult to predict (Gregory *et al.*, 2009).

Rather than trying to examine the potential response to each element of the complex grapevine pathosystem, the present paper proposes a global approach to describe climate vs viticulture pests and diseases relationships. The approach is based on the opportunity offered by the cultivation of grapevine worldwide under a wide diversity of climate conditions. Grapevine pest and disease geography is being documented by a global survey initiated in late 2015. The current paper reports an early analysis of the survey results and presents a method to evaluate the possible evolution of pest and disease management in response to climate change.

Material and methods

1. Viticulture pests/diseases survey

In December 2015, an online survey was sent to researchers, consultants and production professionals (winemakers, vinegrowers, etc.) worldwide. The survey consisted in 4 sections. In sections one to three, the questions focused on the report of 3 diseases or pests considered as the most “important” in the opinion of the interviewees. Additional information concerning spatial extension, frequency of occurrence, management and treatments was collected. Section IV addressed general information concerning the documented area, such as its location, grape products (wine, table grapes, etc.) and vineyard characteristics (training system, irrigation, soil, etc.).

In this study, only the frequencies of answers concerning the #1 to #3 diseases and pests were analyzed. To quantify the pests or diseases according to the concern of the interviewees, a so-called “severity index” (SI) was calculated, globally or for each part of the world, as follows :

$$SI_d = \frac{3N_{1,d}+2N_{2,d}+N_{3,d}}{N_{tot,d}} \qquad (1)$$

where $N_{i,d}$ is the number of answers citing the disease/pest *d* as the number *i* in the reported area (*i*=1 indicating that the respondent considered the disease/pest *d* as the #1 is the reported area), and N_{tot} is the total number of answers collected in the region. Consequently, a SI_d value of 3 indicates that all respondents considered the disease/pest *d* as the number 1.

2. Climate data

Regions documented by the respondents were geolocated using the Vineyard Geodatabase (VGDB). This database was launched in 2012 (Bois *et al.*, 2012) and has recently been updated using wine atlases and maps to locate the major wine growing regions worldwide. The delineation of wine regions was adjusted by analyzing aerial photographs as displayed in Google Earth©. In Europe, the CORINE Land Cover 2006 version (European Environment Agency, 2007) was used to restrict wine regions to areas actually planted with vines. The VGDB, in its current version 1.1.2, references 626 wine growing regions worldwide as a polygon layer.

Amongst the 214 answers collected early 2016 in response to the pest and disease survey, 205 corresponded to regions documented in the VGDB. The remaining 9 were located in regions with small and scattered vineyards. The 205 responses covered 87 VGDB wine growing regions in 26 countries.

Within each polygon of these 87 wine regions, climate data were extracted from the WorldClim 30 sec arc (about 1 km) resolution rasters, version 1 (Hijmans *et al.*, 2005).

WorldClim data provides monthly precipitation (Prec) and minimum (Tmin) and maximum temperature (Tmax) averaged over the 1950-2000 period (hereafter referred to as HIST). To match current climate conditions, WorldClim data was updated to the 2000-2014 period (CURRENT). As the CURRENT period is not available in the WorldClim database, we performed this update using the CRU3.2 gridded monthly database (Harris *et al.*, 2014) providing monthly precipitation and temperature data from 1901 to now. CRU CURRENT minus HIST average was calculated for each month and each climate variable (Prec, Tmin and Tmax). As CRU spatial resolution (0.5 degree) is much coarser than WorldClim's, the resulting delta (CURRENT – HIST difference) was then downscaled by bilinear interpolation to match WorldClim higher resolution.

The downscaled delta was then added to HIST (1950-2000) WorldClim high resolution data.

Climate projections for the mid-21st century (2046-2065 hereafter referred to as FUTURE) by the CNRM (Météo-France ARPEGE) model run under the RCP 4.5 scenario were collected from the WorldClim database at 30 sec arc resolution (see www.worldclim.com for further information on the downscaling methods).

Both CURRENT and FUTURE climate data were used to calculate growing season temperature average (GST ; Jones, 2006) and rainfall (GSR), which correspond to mean (sum) monthly temperatures (rainfall) from April to October in the northern hemisphere and from October to April in the southern hemisphere.

We analyzed GST and GSR distributions in CURRENT and FUTURE climate conditions in the regions where diseases/pests were reported. In this paper the analysis is limited to the 5 diseases/pests exhibiting the highest severity index at a global level (i. e. the most "important" diseases and pests worldwide, according to this survey).

Results and discussion

1. Countries of origin of respondents

Most of the 214 responses analyzed concerned Europe (165), with a large majority of answers (79) from France, provided by wine growers or consultants. 17 answers concerned the United States, 14 South America, 13 Spain, 12 South Africa, 10 Greece, 6 Portugal, 7 Italy, 6 Australia and 5 Israel (Figure 1).

2. Geography of major pests and diseases

At a global level (all 214 responses considered), downy mildew exhibited the first severity index (*SI*=1.74) due to its dominance in Europe (*SI*=2.01). It is closely followed by powdery mildew (*SI*=1.64), which is considered as the most damaging everywhere else (Figure 2). According to *SI*, this disease was the most reported for North America (*SI*=2.11), Australia (2.14) and South Africa (1.92). Grey mold (caused by *Botrytis cinerea*) and Trunk diseases are the third and fourth most reported diseases worldwide (*SI*=0.72 and 0.70, respectively). Grey mold ranks third in Europe (0.99), North America (0.41) and Australia (1) and even first in South America (2.11) where the vine is irrigated. Virus-induced diseases (mostly GFLV fanleaf and GRLaV leafroll-associated viruses) were mostly reported for South Africa (2.08) but also consistently reported for North America (0.29), South America (0.21) and Europe/Mediterranean (0.22).

Amongst other pests and diseases (Figure 2), Flavesence dorée (for Europe/Mediterranean – 0.10 and North America – 0.17), European Grape moth (Europe/Mediterranean – 0.22 and South America – 0.28) and black rot (North America – 0.23) were the most frequently cited.

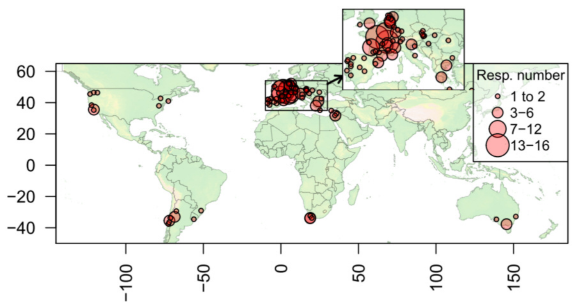

Figure 1 - Spatial distribution of the wine producing regions which interviewees reported diseases from.
The size of the red circles indicates the number of answers collected in each region.

Table 1 - Terms used to describe the climate conditions as function of growing season temperature (GST) and rainfall (GSR). Ranges and classes for GST are taken from Jones (2006). GSR ranges and class names are given based upon a comparison of GSR and the dryness index classes given by Tonietto and Carbonneau (2004).

GST [°C]		GSR [mm]	
Range	Class	Range	Class
< 15	Cool	< 250	Dry
15-17	Intermediate	250-500	Sub-humid
17-19	Warm	> 500	Humid
> 19	Hot		

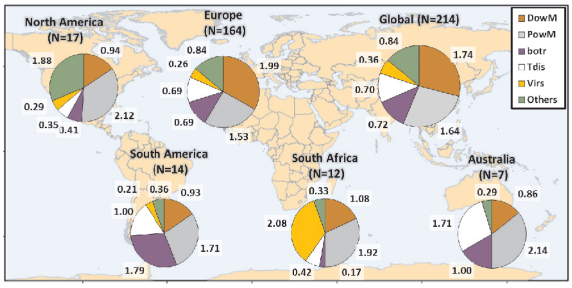

Figure 2 - Severity indices of the main grapevine diseases for each region of the world. DowM: Downy mildew, PowM: Powdery mildew, TDis: Trunk diseases, Botr: Grey mold (*Botrytis cinerea*), Virs: Virus-related diseases.

3. Climate profiles of the most reported diseases

Major diseases (reported as the #1 to #3 diseases by the respondents) exhibited various climate features (Figure 3).

GST and GSR are used to describe the climate conditions with the terms proposed in Table 1. The ranges presented hereafter correspond to the 0.05 to the 0.95 quantiles (thus embracing 90 % of the sample data).

Mildews and grey mold were reported as #1 to #3 diseases in almost all climate conditions met in the regions covered by the survey. Note, however, that grey mold was less frequently reported in dryer conditions. Trunk diseases and viruses were reported in sub-humid to dry regions, within a large range of thermal conditions (Figure 3).

Downy mildew was reported as the #1 disease mostly in intermediate to hot climate with sub-humid to humid conditions: GST from 14.9 °C (0.05 quantile) to 20.3 °C (0.95 quantile) and GSR from 184 mm to 727 mm. This disease was not reported in intermediate and dry climate regions, such as Walla Walla or Yakima Valley (WA, USA; bottom-left of the downy mildew plot in Figure 3). Powdery mildew was reported #1 pest in a larger range of temperature conditions (15.1 to 21.8 °C) with globally lower rainfall during the grape growing season (59 to 675 mm). As for powdery mildew, wide ranges of temperature conditions were associated with areas where grey mold was considered as the number 1 disease: growing season temperature 0.05 and 0.95 quantiles ranging from 14.2 to 21.6 °C. Rainfall in those regions displayed a narrower span (181 to 561 mm). Where trunk diseases were reported as major diseases, climate was either intermediate to hot (15.8 to 20.8 °C) and sub-humid (350 to 500 mm approx.) or hot (19 to 22 °C) and dry to sub-humid (200 to 260 mm). Viruses were also reported in two different types of climates: either intermediate to warm and sub-humid (15 to 18 °C and 350 to 500 mm approx.) or hot (22 to 23.5 °C) and dry (below 250 mm).

For all 5 diseases reported here, the CNRM global circulation model RCP 4.5 scenario projections for 2050 exhibit little expected change in growing season temperature and rainfall conditions from 2000-2014, in comparison to the span of climate condition in which these diseases are currently met. Consequently, no conclusion concerning possible changes in the occurrence of these diseases in the future was proposed on the basis of this preliminary analysis.

Discussion and conclusions

In our survey, pests were seldom reported as major phytosanitary concern in grape growing regions. Cryptogamic diseases were, in contrast, most reported.

While the distribution of diseases differs according to the region of the world, the current analysis suggests that mildews remain the major phytosanitary threat in most of the regions. As the development rate of the powdery mildew agent (*Erysiphe necator*) is mostly temperature driven and rainfall-induced (free water is detrimental to conidia germination; Gadoury *et al.*, 2012), one could have expected little occurrence of this disease in wet and cool climate conditions. In this survey, powdery mildew was reported in extremely diverse climatic conditions, including intermediate and wet regions, probably because of a large tolerance of *Erysiphe necator* to thermal conditions. In contrast, downy mildew is a disease typical of

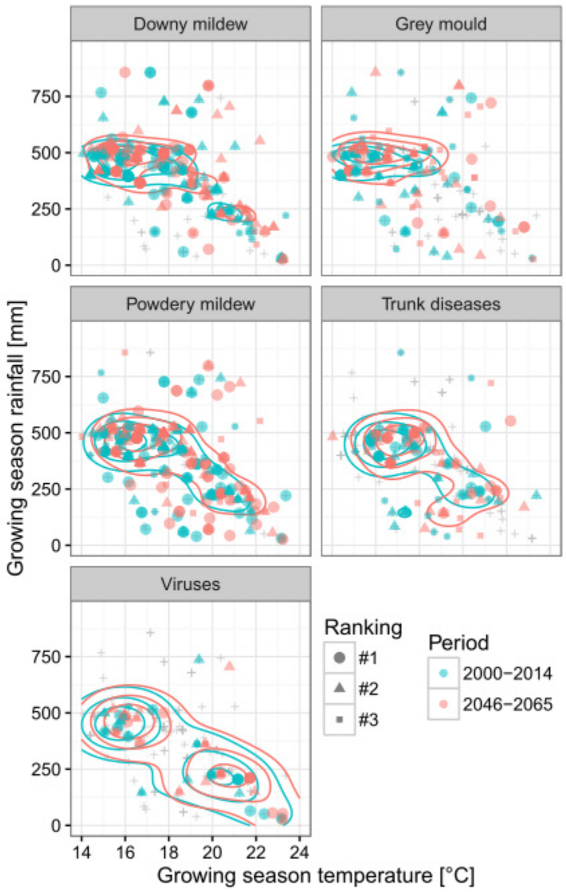

Figure 3 - Distribution of mildews, grey mold, trunk diseases and viruses in each region as function of growing season average temperature and cumulated rainfall of CURRENT (2000-2014, blue color) and FUTURE projected (2046-2065, red color) climate conditions of regions where these diseases were reported as #1 (circles), #2 (triangles) and #3 (squares). The grey "+" locates climate of the regions where the disease was not reported. The contour lines correspond to values that are the most represented (as depicted by a 2D kernel density function).

regions with frequent rainfall (Gessler *et al.*, 2011; Wilcox *et al.*, 2015). However, even in regions with less than 250 mm rainfall during the growing season, downy mildew was reported as the #1 disease by the respondents. Such occurrence might be related to irrigation practices, but also to the fact that downy mildew can be highly damaging and requires a quick response due to its very short cycle. Including such practices (our survey collected information concerning irrigation techniques, quantities and frequency of treatments) together with climate indices calculated on shorter pertinent periods in relation to each pathogen cycle and on its development on bunches may improve our analysis of the risk.

The same observation can be made for grey mold, which was reported as a major disease even in regions where little rainfall is met during the growing season. While rainfall is a key factor for the onset of grey mold (Molitor *et al.*, 2016), other factors such as relative humidity and wind speed may favor *Botrytis cinerea* development on berries (Thomas *et al.*, 1988). In dry climate vineyards, low temperatures are common (high thermal amplitude), possibly favoring dew development on berries. In vineyards where training systems lead to humid grape cluster microclimate, grey mold occurrence could be expected.

Trunk diseases are a growing concern of the grape growers worldwide (De La Fuente *et al.*, 2016), as, contrarily to mildews, the pathogens are not controllable by means of phytochemical products. Many wine production regions around the world reported these diseases as major in our survey. Their link to climate conditions is still unclear and the limited response number in some parts of the world, such as in Australia (N=7), where trunk diseases were reported, is not sufficient to provide any hypothesis concerning the climatic ranges associated with these diseases. The same caution should be observed concerning virus-related diseases, as the role of climate in their occurrence and propagation is certainly minor in comparison to the key role played by plant material selection, breeding, transportation and sanitary control. Moreover, vectors change according to each major virus disease, making it difficult to evaluate the contribution of climate in the extension of such a "group". Note also that some virus-related diseases are difficult (sometimes virtually impossible) to identify through field observations. Consequently, their severity is probably under-estimated in this survey.

The results presented here are preliminary, as some world regions have not been sufficiently documented due to the small number of responses collected. This paper aimed at sharing an original methodology to address the relationship between grapevine disease and pest occurrences and climate. Such documentation is scarce in the current literature. Further analysis is currently being performed, including additional survey answers, climate indices and data (spatial extension, frequency of treatments, etc.) to better depict the challenges of grapevine phytosanitary management in a changing climate.

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What is the expected impact of climate change on wine aroma compounds and their precursors in grape?

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Abstract

The intrinsic quality of a wine is strongly linked with its volatile compound composition involved in the complexity of wine's subtle flavor nuances. Those reminiscent of green pepper, herbaceous, blackcurrant, blackberry, figs or prunes are strongly linked with the maturity of the grapes. Nowadays it is well accepted that macroscopic effects of climate change modify the environmental conditions of grape growing at local scale in all the vineyards across the world. The expected effects on grape and wine production can be positive when they increase the maturity of the grapes, but when the conditions are too warm and too dry they induce opposite effects producing grapes and wines with a lower intrinsic quality. These effects were perceived in young wines but also in older wines kept several years in bottle.

In this article, we provide some examples of effects of climate change and growing conditions on grapevine and wine quality expressed as flavors and antioxidant composition. We also report some results associated with the incidence of grape growing conditions on white and red wine aging potential and on the composition of old wines.

Finally, we discuss the opportunities for vine growers and winemakers to manage the quality of their grapes and wines in this climate change context.

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Introduction

The aromatic component of wine is a decisive criterion of its sensory quality. This quality is based on the perception of aromatic nuances of varying intensity and complexity, often associated with the expression of a single grape variety or a mixture of grape varieties that is modulated by the soil and can thus contribute to the recognition of a typical or sensory identity (another word for typicality). The aromatic component is due to the presence in wine of many volatile compounds from families that contribute to the perception of aroma thanks to their vegetal, floral or fruity notes, or through complex sensory phenomena involving a mixture of the volatile compounds. Moreover, the preservation of this typical aromatic component during wine aging, possibly enriched by a «reducing» aging bouquet over time, is the signature and specificity of wines made from grapes that have ripened in temperate climates.

The prospects of climate change over the next century raise questions about the potential impact of a global rise in average temperature on the aromatic potential of grapes and wine quality. This paper presents current knowledge about the impact of various eco-physiological parameters of the vine on the aromatic compounds of wines; the consequences likely to be observed for wines in the context of climate change are also discussed.

1. The aromatic component of wines

The aromatic nuances perceived when wines are tasted result from a combination of volatile compounds, at least fifty, in the headspace above a glass of wine. These compounds act as stimuli at the olfactory epithelium level before being converted into nerve impulses and becoming sensations in the mind (Shepherd, 2006). In the last forty years, almost 1,000 volatile compounds have been identified in wine; their contents range from several hundred milligrams per liter to levels likely below ten picograms per liter. The odor thresholds of these compounds are also highly variable and are mostly found in the picogram range and up to a dozen milligrams per liter for less odorous compounds. Thus, certain trace compounds can play an important role in wine aroma, while other much more abundant compounds yet play a minor role.

A distinction has to be made between the groups of volatile compounds contributing to wine aroma. First, there are the strictly fermentative compounds produced by wine microorganisms (S. cerevisiae yeast, lactic acid bacteria) involved in the floral, fruity and milky notes of young wines, especially the major ethyl esters of fatty acids and higher alcohol acetates. Next, there are the compounds produced by the secondary metabolism of grapes present in wines such as derivatives of carotenoids [ß-damascenone (apple sauce, floral), ß-ionone (floral, violet), TDN (1,1,6-trimethyl-1,2-dihydronaphtalene; notes of kerosene), vitispirane (woody nuances, camphor)], lactones (fruity, coconut, peach and apricot) and furanones (caramel, cooked sugar). This group also includes those specifically associated with the aroma of certain varieties: for example, monoterpenes, which contribute to floral characteristics of Muscat varieties, or sesquiterpenes such as (-) rotundone, which contribute to notes of black pepper. Volatile thiols (sulfur-containing compounds with grapefruit boxwood notes or passion fruit) are involved in the typical aroma of Sauvignon blanc wine and many white and red varieties like Colombard, Chenin, Gewürztraminer, Semillon, Petit Manseng, Arvine, Merlot, and Cabernet-Sauvignon. Certain compounds of this family can contribute to the toasted notes associated with wine aging bouquet. A member of the methoxypyrazine family, 2-methoxy-3-isobutylpyrazine (IBMP), reminiscent of green pepper and pea pod, contributes also to the flavor of grapes and wines. Most of the compounds exist as precursors in fruits: volatile hydroxylated forms (e.g. polyols with little odor) or glycosides for monoterpenes and norisoprenoid C13 derivatives, S-conjugated forms for thiol precursors, Maillard reaction products (furanones) and lipid derivatives (lactones). Except for methoxypyrazines, their concentrations increase in grapes during ripening depending on the prevalent climatic conditions (temperature, light), the availability of water and organic/inorganic compounds, and the physiological characteristics of the vines. The formation of these compounds is associated with chemical and enzymatic reactions which depend on the physiological state of the berry and the eco-physiological conditions of the vine. Knowledge of these reactions is still fragmentary (Schwab and Wüst, 2015).

2. Temperature/light relationship and the aromatic component of wines

The primary consequence of an increase in average temperature during grape ripening is that the herbaceous vegetal notes of wines are limited. These notes are linked in part to the methoxypyrazines, especially IBMP. Like other pyrazines of the same family, IBMP evokes hints of unripe green bell pepper and pea pod, and it is a varietal trait of wines vinified from unripe grapes from the Carmenet family, in particular Cabernet franc, Fer Servadou, Cabernet-Sauvignon, Carmenère, Merlot and Sauvignon blanc. The work of Allen and Lacey (1993) and Falcao *et al.* (2007) showed that IBMP levels in wines are lower when the temperature is higher during the growing season. This phenomenon is amplified by exposure of the grapes to light and the removal of the basal leaves that contain IBMP during the nouaison-grape closure stages of the vine (Ryona *et al.,* 2008; Gregan *et al.,* 2012.). Conversely, the IBMP content is higher in grapes from vigorous vines with a high vegetation density (Allen and Lacey, 1993). However, as is sometimes observed, water stress, which can contribute to stuck ripening, may lead to grapes with IBMP concentrations that negatively impact the aromatic component of wines.

On the other hand, the concentrations of carotenoid derivatives, especially C13-norisoprenoid derivatives, are higher whenever grapes are more exposed to light and high temperature. This leads to a greater breakdown of grape carotenoids between veraison and maturity. In particular, TDN, a compound involved in the kerosene notes of Riesling wines and synthesized during bottle aging from non-volatile precursors, is more abundant in wines elaborated from grapes ripened in warmer climates (Marais *et al.,* 1992b). Nevertheless, this is not always the case for other C13-norisoprenoid derivatives such as ß-damascenone, contributing to fruity notes in wines, given the complexity of the reaction mechanisms in the berries leading to the formation of this compound from precursor forms. In fact, two authors reported lower concentrations of ß-damascenone in white varieties in conditions of exposure to light and higher temperature (Marais *et al.,* 1992a; Kwasniewski *et al.,* 2010). In general, most studies on the aromas and aroma precursors of fruity and floral nuances (monoterpenes) underline the benefit of higher temperatures during ripening but also their negative effect on fruit metabolism whenever they are excessively high.

Recently, a study was carried out in Bordeaux on the aromatic component of red wine from overripe black grapes (notes of jammy fruit, prune, dried fig). It was demonstrated that these wines have a greater abundance of chemical compounds belonging to the furanones (candy, caramel flavors) and lactones and showed the contribution of these compounds to these aromatic notes (Allamy *et al.,* 2015; Allamy *et al.,* 2016). Moreover, the analysis of different vintages from a Pomerol estate containing a high percentage of Merlot showed higher concentrations of massoia lactone (dried figs and coconut flavors) and γ-nonalactone (coco, cooked peaches) during years with higher average temperatures, such as 2003 vintage (Figure 1). For this vintage, concentrations reached the detection threshold of these compounds, with 10 µg/L and 27 µg/L for massoia lactone and γ-nonalactone, respectively. Presumably, increased perception of overripe fruity notes, as occurs in very hot vintages, is one of the consequences to be expected from global warming.

It is interesting to compare these values to those found in "traditional" warm climate, where vines were irrigated, such as in Napa Valley (California). As depicted in Figure 2, average values of the last eight vintages were close to the γ-nonalactone concentration of 2003 vintage in Bordeaux. In these red wines, lowest concentrations were found in 2011 vintage; a cool and wet vintage in Napa.

3. Vine water status: an additional parameter influencing the aromatic potential of grapes

One of the indirect consequences of global warming is a change in the water status of the vine, which will obviously impact the physiology of the plant (van Leeuwen and Darriet, 2016) and the biosynthesis of aromatic compounds and their precursors. Regarding the volatile thiol precursors, a link has been established between the presence of moderate vine water deficit and the accumulation of S-conjugate precursors, water deficit leading to shoot growth cessation and the accumulation of secondary metabolites in the berry. Conversely, severe water deficit affects the ripening of the grapes and leads to a lowering of volatile thiol precursor levels in grapes (Peyrot des Gachons *et al.,* 2005).

The work of Armin Schüttler (2012), conducted at the Geisenheim Institute on the Riesling variety for several years and at the same site, investigated the impact of vine water status and various thinning practices on several chemical families (monoterpenes, volatile thiols, norisoprenoid C13 derivatives). The main finding was that the effects of water deficit on the aromas and flavor precursors in grape vary according to the family of aromatic compounds considered

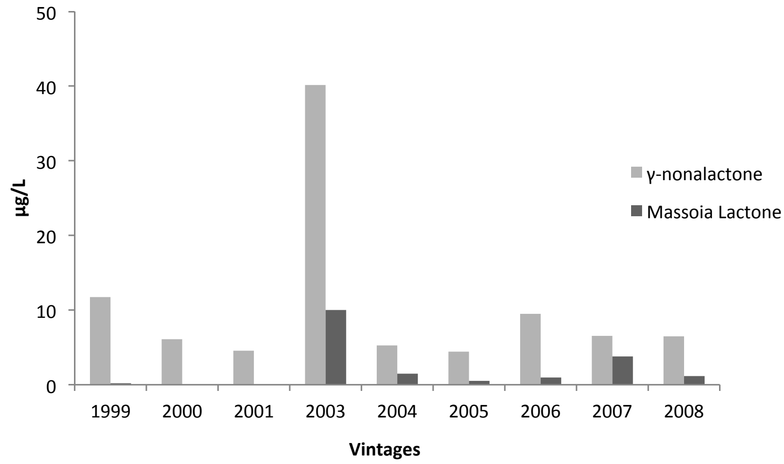

Figure 1 - Content of massoia lactone and γ-nonalactone in Pomerol red wines from the same estate (Bordeaux) between 1999 and 2008 (Pons *et al.,* 2011, and Personal results).

Analyses were performed in 2011.

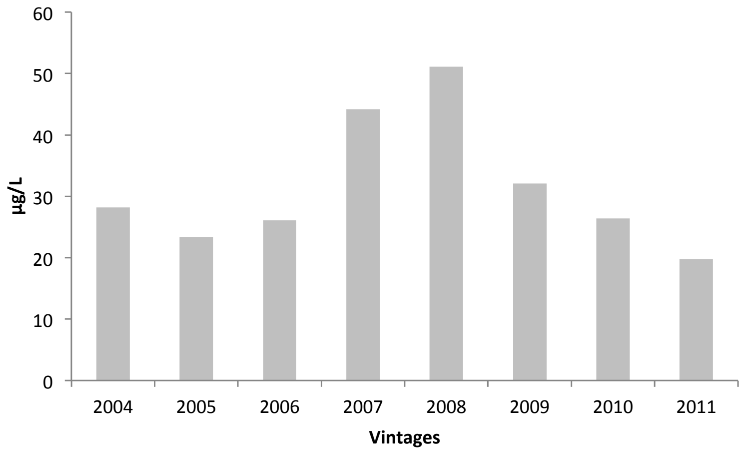

Figure 2 - Content of γ-nonalactone in red wines from the same estate (Napa Valley) between 2004 and 2011.
Analyses were performed in 2013.

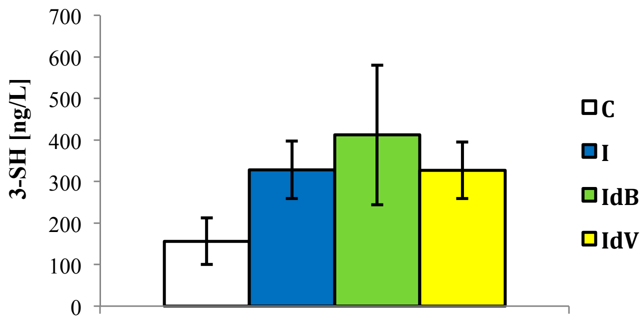

Figure 3 - 3-sulfanylhexan-1-ol (varietal thiol) content in wine in 2009 vintage as a function of water deficit and cluster exposure. (C) non-irrigated modality with water deficit that was strong in 2009; (I) irrigated modality with water deficit that was moderate in 2009; (IdB) modality with irrigation and early thinning; and (IdV) modality with irrigation and thinning at veraison.
The water deficit modalities are identical to modalities (I), (IdB) (IdV) (according to Schüttler *et al.,* 2011, 2013).

(Schüttler *et al.,* 2011, 2013). For example, as depicted in Figure 3, 3-sulfanylhexanol (3SH) levels in wines analyzed in 2009 were not significantly changed by thinning and improved cluster exposure, whether early or late, while the volatile thiol content was much lower when water deficit was high, as Peyrot des Gachons *et al.* (2005) had previously observed. For this reason, a water regime that is too restrictive requires adaptation of the plant material.

Regarding (-) rotundone, a compound associated with notes of black pepper in Syrah wines and playing a role in the aroma of the Duras variety, the work of Scarlett *et al.* (2014) also showed a lower content of this compound in wines from vines having faced greater water deficit.

Thus, the cumulative effects of temperature and more restrictive water status cause a change in the metabolism of fruit that can sometimes lead to stuck ripening. For this reason, the effects of water deficit on the biosynthesis of the aromatic potential of grapes could be more pronounced in conditions where nighttime temperatures remain high. It is therefore important to investigate more precisely in the years to come the direct consequences and the extent of these expected changes, not only on the aromatic potential of grapes but also on the quality and sensory perception of wines.

4. Wine aging potential

The modification of the aromatic potential of grapes during ripening is also likely to influence the biosynthesis of other berry metabolites such as phenolic compounds and glutathione, which impact the aromatic component by their reactions. Thus, during dry years, Sauvignon blanc grapes are richer in flavan-3-ols (tannins) and less rich in glutathione, an important antioxidant for reducing the risk of premature aromatic aging of grapes and wines. Analysis of Sauvignon musts from the same winery showed significant differences in glutathione levels in grapes, with lower levels in hot (2003) and dry (2005) years (Pons *et al.,* 2015; Figure 4).

5. Adaptive strategies

Over the past 20 years, vine physiology has been advanced in temperate-climate vineyards because of higher

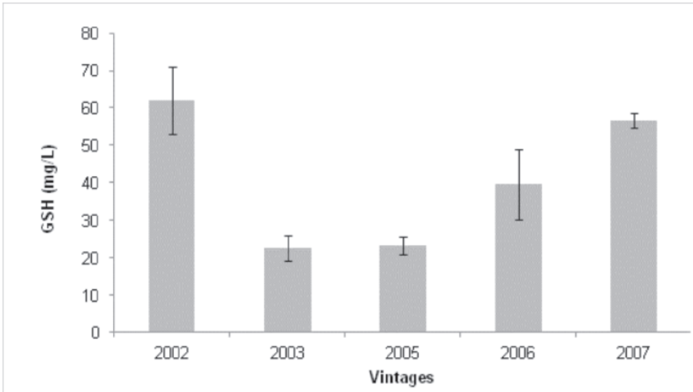

Figure 4 - Average glutathione content in must of Sauvignon blanc grapes harvested at maturity in two vineyards in the Graves region (Bordeaux) for the years 2002 to 2007 (Pons *et al.*, 2015).

temperatures and at the same time growers have increased the delay between veraison and harvest (so-called "hang-time"; van Leeuwen and Darriet, 2016). Hence, the vegetal traits related to a lack of grape maturity are now less perceived and winemakers can craft wines that express their full potential of floral and fruity notes, combined with freshness and sometimes cooked fruit. Climate change is likely to impact significantly both the organoleptic characteristics of wines and their aging potential, in particular by reducing the level of acidity in grapes and wines.

Care in choosing harvest dates and adapting trellising modes (limiting thinning, managing mineral and nitrogen nutrition, making sure that the plant's vigor is sufficient and that water deficit is not excessive) is the primary adaptive means for preserving the aromatic potential of grapes. Furthermore, promoting clonal diversity within varieties can be a starting point for adaptation. If climate change were to become very extreme, non-local later-ripening varieties could offer alternatives once their potential to reveal the diversity of terroirs in their aromatic and flavor components has been assessed. A major issue concerns changes in rainfall patterns and their potential impact on the development of pathogens. Thus, in a context of limited or significant change in climatic conditions, researchers and experimenters should now analyze the specific consequences of these multifactorial phenomena on the aromatic and flavor components of wines and their aging potential. Work in this direction is now underway at ISVV (Drappier *et al.,* 2016; Wu *et al.,* 2016).

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

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Abstract

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

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

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

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

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

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Introduction

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

Consequences of climate change on viticulture

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

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

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

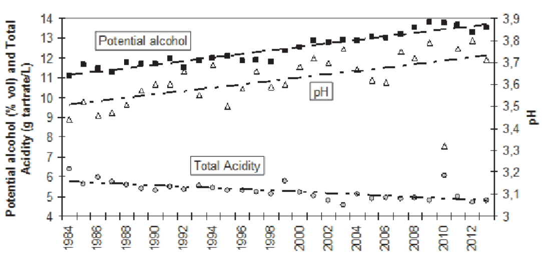

Figure 1 - Potential alcohol levels, Total Acidity and pH of grape juice just prior to harvest in Languedoc from 1984 to 2013 (data: Dubernet laboratory, F-11100 Monteredon-des-Corbières).

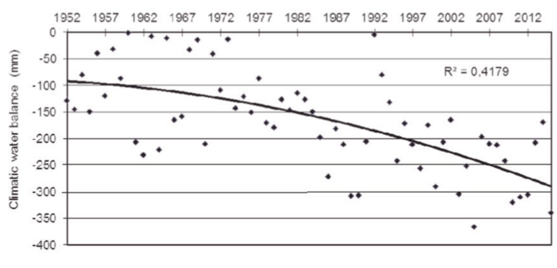

Figure 2 - Evolution of water balance from 1952 to 2015 calculated between April 1 and September 30 for the Saint-Emilion region (France).
Water balance model according to Lebon *et al.* (2003).
Parameters: Soil Water Holding Capacity = 0 mm; no stomatal regulation.

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

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

Possible adaptations to increased temperatures

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

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

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

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

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

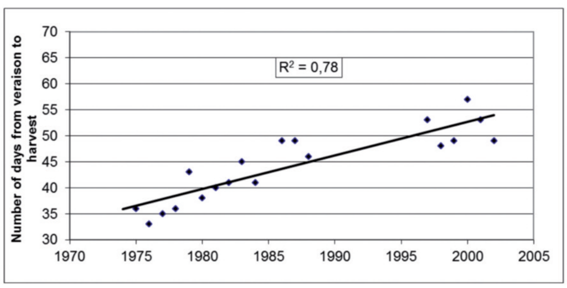

Figure 3 - Number of days from veraison to harvest for a block of Cabernet-Sauvignon in the appellation Margaux, from 1975 to 2002 (data ISVV, Guy Guimberteau and Laurence Gény).

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

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

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

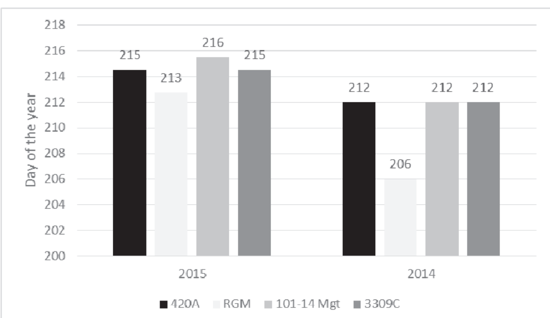

Figure 4 – Day of the year for 50% veraison for Merlot grafted on 4 different rootstocks in the Saint-Émilion area (Bordeaux, France) in 2014. Boehler and van Leeuwen, unpublished results.

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

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

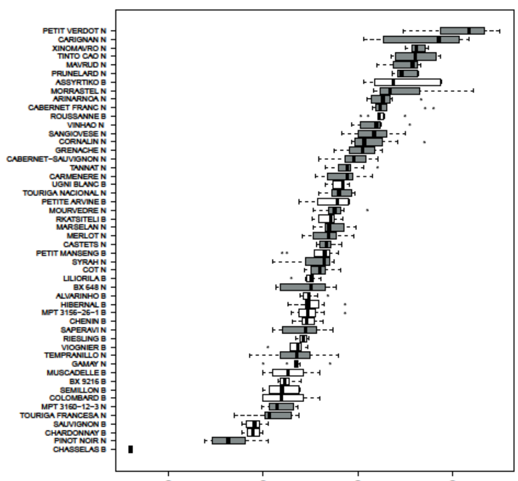

Figure 5 - 50% veraison dates for 52 cultivars in the VitAdapt experiment in 2014 (day of the year). Data are averages of 4 replicates.

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

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

Possible adaptations to increased drought

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

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

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

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

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

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

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

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

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

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

Possible adaptations to increased radiation

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

Conclusions

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

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Local-based approach for assessing climate change adaptation in viticulture

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Abstract

With a changing global climate, the viticulture sector faces many environmental and socio-economic challenges. Given the perennial nature of grape growing, winegrowers will need to develop adaptation strategies that deal with both short-term climate variations and long-term climate changes while accounting for local vulnerability in order to avoid mal-adaptation. Here we aimed to enhance the assessment of climate change adaptation in viticulture by undertaking a local-based approach that specifically focuses on the spatial understanding of local variability in environmental conditions and grapevine behavior, as well as the evaluation of winegrowers' decision-making processes and management practices. The methodological framework used in this study was applied to two regulated wine producing areas located in the Anjou-Saumur wine growing sub-region, France. Results have highlighted the importance of undertaking studies at terroir scales in order to better define the spatial variability of local climate and its influences on grapevine behavior, and frame local climate vulnerability and winegrowers' adaptive processes. Within the context of climate change and the key issues surrounding adaptation, local-based studies should allow a greater understanding of the potential future impacts of climate change and adaptation strategies necessary at different spatial and temporal scales.

Keywords: Climate change, local scale, adaptation, viticulture, vulnerability

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Introduction

Long-term climate change, together with its actual and expected impacts on natural and human systems, has received considerable attention in the last few years (IPCC, 2014). For most wine growing regions, significant trends in regional climates, and in particular surface temperatures, have been observed (Jones and Davis, 2000; Duchêne and Schneider, 2005; Tomasi *et al.*, 2011; Neethling *et al.*, 2012; Koufos *et al.*, 2014). These studies also indicated important changes in grapevine phenology and grape composition, with the latter leading to increased alcohol levels and altered wine sensory profiles (de Orduña, 2010; Fraga *et al.*, 2012). Although those changes in grapevine behavior are partly attributed to evolving practices, recent warming trends and declining soil water contents have been major causal factors (Webb *et al.*, 2012).

Hence, continued climate change is very likely to have significant effects on regional wine quality and style, which over the long term may cause geographical shifts in suitable grapevine varieties and production areas (Kenny and Harrison, 1992; Schultz and Jones, 2010). Adaptation to climate change is therefore unavoidable, becoming an immediate priority in the viticulture sector. Indeed, vineyards planted over the next decade, and remaining economically productive for many years, will be exposed to projected long-term climate changes. For France, it is likely that unprecedented climate conditions will be experienced by the middle of this century, moving outside the bounds of historical climate variability (Mora *et al.*, 2013).

To that end, several adjustments can be made. For example, changes in cultural practices related to vigor and soil management, use of more drought and heat tolerant plant material (Barbeau *et al.*, 2014) or more drastically, expansion of viticulture to non-traditional wine growing regions (Hannah *et al.*, 2013). However, effective adaptation strategies and policies should be developed based on a better understanding of the characteristics of the local environment (Quénol, 2014). This is of particular importance in the viticulture sector as grape and wine quality are much attributable to the unique characteristics of their geographical location (White *et al.*, 2009; Metzger and Rounsevell, 2011), where winegrowers' decision-making plays a significant role (Van Leeuwen and Seguin, 2006; van Leeuwen *et al.*, 2013). Indeed, failure to account for those local factors and processes that define exposure, sensitivity, and adaptive capacity to changing conditions will lead to an incorrect assessment of potential climate change impacts and importantly, necessary adaptation strategies at different temporal and spatial scales (Holland and Smit, 2010).

In response to greater climate changes, new climate and soil conditions will provide the most effective adaptation solutions (Nicholas and Durham, 2012). Therefore, local-based studies contribute to the understanding of fine-scale environmental diversity and complexity (Quénol, 2014). In assisting winegrowers in framing adaptation responses to climate change impacts, understanding of local climate and soil variability should provide winegrowers with solutions to attenuate significant changes in wine quality and typicality, while still remaining within the boundaries of current production areas. Indeed, vineyard plots currently considered less qualitative or limiting for optimal grapevine behavior could in the future become more favorable for grape and wine production (Coulon-Leroy *et al.*, 2014).

Within this perspective, this study undertakes a local-based approach aimed to enhance the assessment of climate change adaptation in viticulture. The study uses a methodological framework that specifically focuses on the spatial understanding of local variability in environmental conditions and grapevine behavior, as well as the evaluation of winegrowers' decision-making processes and management practices.

Study area

The study was conducted in the Anjou-Saumur wine growing sub-region, located in the North West of France (Figure 1a). At local terroir scales, two experimental sites were selected within the vineyards of: i.) AOP Coteaux du Layon, a sweet wine producing area where Chenin is the main variety (Figure 1b.) and ii) AOP Saumur Champigny, a red wine producing area where Cabernet franc is the main variety (Figure 1C). The study site in Coteaux du Layon had a surface area of about 900 ha (~3 km x 3 km), and in Saumur Champigny, a surface area of about 1600 ha (~4 km x 4 km).

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

Material and methods

1. Environmental data and viticultural measurements

Within each study area, a network of weather stations, temperature data loggers and rain gauges were installed according to the diversity in terrain (relief, aspect, etc.) and geo-pedological characteristics (soil texture, water holding capacity, etc.). Weather stations were located in an open space close to the vineyards, whereas the temperature data loggers were installed within the vineyard plots. For this study, a 25m Digital Elevation Model was used, and digital soil data and characteristics (scale of 1:10 000) were obtained from the Cellule Terroir Viticole (CTV). For temperature data loggers, measurements were realized every 15 minutes and averaged to obtain hourly data. Weather stations and rain gauges measured data every hour. After the explanatory analysis of raw data (i.e. quality data control), daily minimum and maximum temperatures were calculated according to the standard of Météo France. Daily mean temperatures were calculated as the mean of the daily minimum and maximum temperatures.

Measured daily climate data from, 2013 to 2015 were then used to calculate various climate variables and bioclimatic indices related to grapevine growth and berry ripening (Table 1). It should be noted that these indices were calculated annually, and were therefore modified compared to the required conditions (i.e. 30-year climate datasets measured at 2 m by a standard weather station). In order to assess how local topography influences climate variability, the statistical relationships of terrain parameters on calculated climate variables were evaluated.

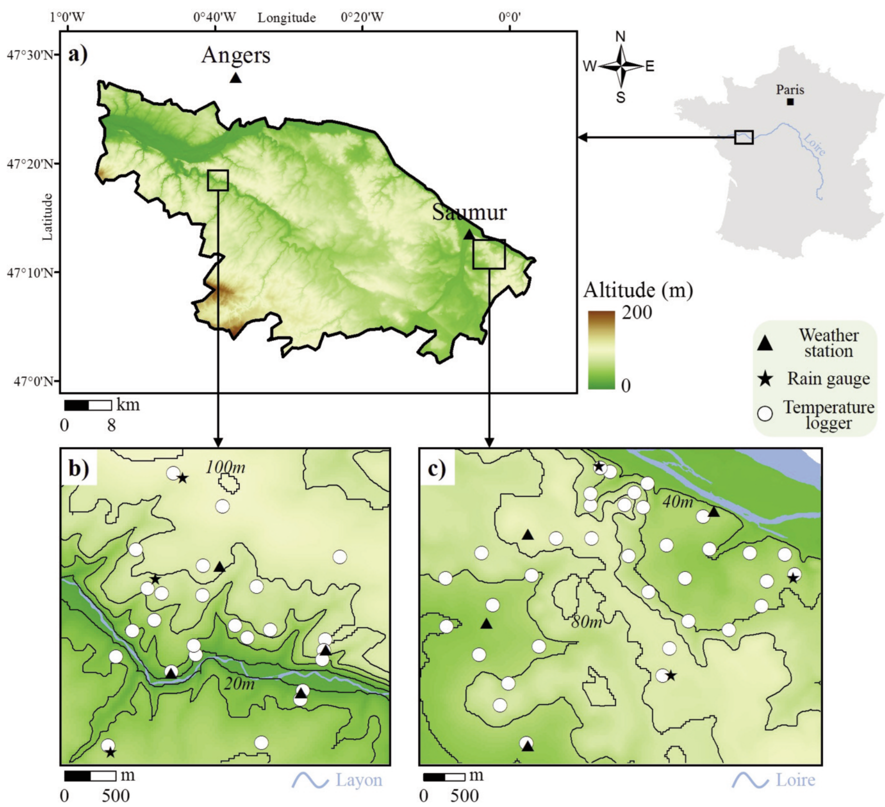

Figure 1 - The Anjou-Saumur wine growing sub-region, France (a) and position of the two study areas in the AOP Coteaux du Layon (b) and the AOP Saumur Champigny (c).

Table 1. Viticultural agroclimatic indices calculated for each study area.

Agroclimatic Indice	Acronym
Mean growing season temperature[a]	GST (°C)
Total growing seasonal rainfall[a]	GSR (mm)
Growing degree days[a, b]	GDD (°C units)
Huglin Index[c]	HI (°C units)
Cool Night Index[c]	CI (°C)
Dryness Index[c]	DI (mm)

[a]Calculated from 1 April to 30 September
[b]Winkler *et al.*, 1974; Base temperature of 10 °C.
[c]Tonietto and Carbonneau, 2004

To assess the spatial variability in grapevine behavior, viticultural measurements were carried out on 12 plots of Chenin in the Coteaux du Layon study area and 12 plots of Cabernet franc in the Saumur Champigny study area. These vineyard plots had similar training systems, and each plot was equipped with a temperature data logger. During the growing season, phenological observations were made (flowering, véraison), and during the ripening period (September), berry composition was analyzed on a weekly basis as well as the isotopic ratio of carbon 12 and 13, just before harvest. The isotope ratio (Δ13C in ‰) permits to assess the level of plant water stress during the ripening period (Van Leeuwen *et al.*, 2009). The greater the water stress, the higher the proportion of carbon 13 in the berries. The values vary between -20 and -27‰, where -20 indicate a high water stress and -27 an absence of water stress.

2. Semi-structured interviews

Fifteen winegrowers were selected from each study area according to their seniority, geographical position, farm size, and whether the wine farms were family owned or privately held. Regarding differences in production strategies, there were four conventional, seven integrated, and four organic farms from Coteaux du Layon and five conventional, seven integrated, and three organic farms from Saumur Champigny. Individual semi-structured interviews were conducted with the thirty selected winegrowers. This research technique consists of many open-ended questions, with the objective of collecting and understanding participants' experiences and opinions on a particular event or topic (Rubin and Rubin, 2005). Prior to individual interviews, conducted at participants' wine farms, pre-test interviews were completed with two additional winegrowers to ensure that the questionnaire met research goals.

The questionnaire developed covered four themes. The first theme focused on general wine farm information (e.g. grapevine varieties, wine styles). The second theme focused on changing viticultural practices over recent decades. Winegrowers were asked to describe how annual and perennial practices have evolved at farm- and plot-level, including identifying the possible causal factors for those changes. The third theme focused on climate-related perceptions and experiences over the last, 20 years. Winegrowers were asked to identify the favorable and unfavorable climate conditions for grapevine behavior and wine production. In addition, they were asked to describe their adaptive responses to those conditions, which, according to Smit and Skinner. (2002), vary depending on their timing (i.e. reactive or anticipatory) and duration (i.e. tactical/short-term or strategic/long-term). The final theme focused on winegrowers' perceptions of climate change. Winegrowers were asked to comment on recent climate changes and their impacts on grapevine behavior and wine production. From here, they were asked about future climate change, its potential impact and their view on necessary adaptation strategies.

Results

1. Spatial variability in daily and seasonal climate variables

During the growing seasons (i.e. April to September) of 2013 to 2015, a strong spatial variability in mean growing season temperatures (GST) was observed. From 2013 to 2015, GST varied by 0,7°C, 0,8°C and 0,6°C respectively in Coteaux du Layon (Table 2). For Saumur Champigny, GST varied by 0,7°C, 1,1°C and 1,1°C from 2013 to 2015. Bonnefoy *et al.* (2013) have shown that this observed spatial variability in seasonal temperatures at local scales can be as significant as the seasonal temperature variability at larger scales, such as between two large regions. This result has also been supported by those of the ANR-TERVICLIM and GICC-TERADCLIM projects, which conducted fine-scale climate studies in many wine growing regions worldwide (Quénol, 2014).

During extreme temperature events such as risk of spring frost, an even greater spatial variability in temperatures was observed. For example on April 29, 2013, during a spring frost event, minimum temperatures varied from -1,0°C to 3,2°C (difference of 4,2°C) in Coteaux du Layon, and from -1,9°C to 2,9°C (difference of 4,8°C) in Saumur Champigny. During this event, minimum temperatures in Coteaux du Layon were principally influenced by altitude, resulting in the lowest minimum temperatures recorded at low elevations. Though altitude also significantly affected minimum temperatures in Saumur Champigny, the proximity of the Loire River played an important role in moderating minimum vineyard temperatures. Vineyards situated close to the Loire River recorded warmer minimum temperatures than vineyards located further away, at same altitude levels. During hot summer days, with a tendency towards heat waves, daily maximum temperatures also varied strongly over space, yet not as significantly as minimum temperatures previously described. For example on July 22, 2013, daily maximum temperatures varied from 35,5°C to 37,7°C (difference of 2,2°C) in Coteaux du Layon, and from 35,3°C to 38,8°C (difference of 3,5°C) in Saumur Champigny. The respected influence of environmental variability on maximum temperatures was also much more complex. In general, maximum temperatures were positively correlated with slope steepness in Coteaux du Layon, whereas maximum temperatures in Saumur Champigny were more related to landscape openness, calculated using the IFP index (Jacquet and Morlat , 1997). Consequently, the warmest seasonal and daily maximum temperatures were observed in vineyards characterized by a sheltered landscape (large trees, woodlands, forest, etc.), minimizing airflow and increasing ambient air temperature.

2. Spatial variability in bioclimatic indices

Bioclimatic indices are frequently used to represent and describe viticultural climates worldwide, where they are related to suitability of varieties as well as wine quality and style (Tonietto and Carbonneau, 2004). For both study areas, the strong spatial variability in seasonal temperatures was reflected on the spatial variability in calculated bioclimatic indices (Table 2). For these indices, differences are first related to the geographical position of each study area, where Saumur Champigny is generally warmer and wetter than Coteaux du Layon. The seasonal conditions of each vintage also explain the differences in bioclimatic indices between, 2013 and, 2015. According to the mean GDD and HI values, 2015 was the warmest and, 2013 the coolest. In the Coteaux du Layon, 2013 was the driest, while, 2015 was the driest in Saumur Champigny (i.e. based on DI values).

Yet, it emerges that these indices vary significantly among the vineyard plots according to the characteristics of local environmental conditions. For example in 2013, certain vineyard plots were

Table 2. Spatial variability in climate variables and bioclimatic indices in the study areas of Coteaux du Layon and Saumur Champigny.

	2013				2014				2015			
Bioclimatic Indices	Mean[a]	Min[a]	Max[a]	Δ[b]	Mean[a]	Min[a]	Max[a]	Δ[b]	Mean[a]	Min[a]	Max[a]	Δ[b]
Coteaux du Layon[d]												
GST (°C)	16,4	16	16,7	0,7	16,9	16,4	17,2	0,8	17,1	16,7	17,3	0,6
GSR (mm)	292	277	310	33	325	291	342	51	*332*[c]	*327*[c]	*342*[c]	*15*[c]
GDD (°C units)	1218	1151	1280	129	1256	1181	1323	142	1298	1226	1353	127
HI (°C units)	1781	1729	1871	142	1861	1803	1936	133	1918	1849	2031	182
CI (°C)	11,3	9,7	12,1	2,4	11,6	10	12,5	2,5	9,8	8,3	10,5	2,2
DI (mm)	-111	-159	-28	131	-74	-125	7	132	-96	-145	-8	137
Saumur Champigny[e]												
GST (°C)	16,7	16,3	17	0,7	17,1	16,5	17,6	1,1	17,6	16,9	18	1,1
GSR (mm)	364	331	402	71	381	342	407	65	*324*[c]	*317*[c]	*334*[c]	*17*[c]
GDD (°C units)	1273	1192	1324	132	1310	1195	1388	193	1391	1279	1477	198
HI (°C units)	1836	1752	1914	162	1907	1836	1977	141	2019	1942	2101	159
CI (°C)	11,8	10,3	12,6	2,3	11,8	9,4	12,8	3,4	10	8,7	10,9	2,2
DI (mm)	-22	-78	39	117	-6	-65	56	121	-41	-96	26	122

[a]Mean, minimum and maximum values obtained from the network of climate instruments for each study area
[b]Difference between the minimum and maximum values (i.e. range)
[c]Lack in complete data from all rain gauges and weather stations
[d]Study site in Coteaux du Layon had a surface area of about 900 ha (~3 km x 3 km)
[e]Study site in Saumur Champigny had a surface area of about 1600 ha (~4 km x 4 km)

(GDD, HI, CI) and other climate-related variables, in particular soil water supply (DI), are well documented and integrated in the decision-making process of annual and perennial practices.

3. Spatial variability in grapevine behavior

Viticultural observations illustrated important differences in the timing of phenological stages and in berry composition during the ripening period (Table 3). In Coteaux du Layon, differences of 4 to 6 days for flowering and 6 to 9 days for véraison were recorded, from 2013 to 2015, whereas in Saumur Champigny the differences were 3 to 5 days for flowering and 7 to 12 days for véraison. These differences were even more significant during the ripening period, particularly in comparing maturity indices (TSS/TA ratio), 5 weeks after the mean date of véraison for all vineyard plots. In Coteaux du Layon, the differences varied from 17,5 to 28,0 over the, 2013-2015 period, while in Saumur Champigny the differences varied from 9,7 to 19,1. Consequently, a strong spatial variability in grapevine behavior is observed at local terroir scales. For example in Coteaux du Layon, some vineyard plots were in the normal ripening stage, whereas others had already reached the over-ripening stage, either through the process of "passerillage" (on-vine grape drying) or noble rot (botrytised grapes).

In order to understand the impact of climate conditions on grape composition, the linear relations between two measured berry components (i.e. sugar content and total acidity) and bioclimatic indices were studied. The results for Cabernet franc in Saumur Champigny are presented in Figure 2. For both experimental sites, results illustrate that climate influenced the content in soluble sugars (g/L) and total acidity (g/L). The strongest relationships were observed with the calculated temperature-based indices of Growing Degree Days (GDD) and Growing Season average Temperatures (GST). In this context, vineyard plots with greater heat accumulation were characterized by higher levels in soluble sugars, while having lower concentrations in total acidity. Similar results were observed for the relationship between Huglin Index values and the respective concentrations in sugars and total acidity. Indeed, warmer growing season temperatures allow the grapevine to function more frequently at optimum temperature thresholds for vine photosynthesis and hence favor the accumulation of sugars in grape berries. By contrast, the metabolism of total acidity, and more importantly malic acid, is greatly affected by temperature fluctuations, where elevated temperatures enhance the respiration of malic acid during berry ripening. As respiration takes place during the day and at night, night temperatures are also key factors influencing total acidity levels. Considering therefore the influence of night temperatures during ripening on total acidity via the Cold night Index (CI), expected results were observed (e.g. in Saumur Champigny, R^2=0.40), meaning that cooler nighttime temperatures lead to higher concentrations in total acidity. While viticultural indices were elaborated for regional studies, where climate data are obtained over long periods and from normalized weather stations, these results show that they can provide important information about grapevine behavior at local vineyard levels.

Table 3. Spatial variability in grapevine behavior in the AOP Coteaux du Layon (variety: Chenin) and AOP Saumur Champigny (variety: Cabernet franc).

	2013				2014				2015			
Vine behavior	Mean[a]	Min[a]	Max[a]	Δ[b]	Mean[a]	Min[a]	Max[a]	Δ[b]	Mean[a]	Min[a]	Max[a]	Δ[b]
Coteaux du Layon												
Mid-flowering (Jd)[c]	183	181	185	4	166	164	168	4	163	160	166	6
Mid-véraison (Jd)[c]	244	241	247	6	232	230	236	6	226	222	231	9
Maturity index[d]	29,9	21,3	38,8	17,5	36.9	25	53	28	35,3	25,7	45	19,3
Δ13C (‰)	-24,1	-20,4	-26,7	6,3	-27,5	-25,3	-28,7	3,4	-26,4	-24,5	-28	3,5
Saumur Champigny												
Mid-flowering (Jd)[c]	179	178	181	3	162	160	165	5	159	157	161	4
Mid-véraison (Jd)[c]	246	243	250	7	234	231	239	8	227	223	235	12
Maturity index[d]	32,5	28,9	37,1	9,7	36,8	32,8	43,2	10,4	45,4	37,1	56,2	19,1
Δ13C (‰)	-25	-22,9	-26	3,1	-27.4	-26,1	-28,6	2,5	-26,4	-24,8	27,3	2,5

[a]Mean, minimum and maximum values obtained from the network of vineyard plots for each study area
[b]Difference between the minimum and maximum values (i.e. range) ; [c]Dates are in Julian days (Jd)
[d]Maturity index = the sugar content (g/L) to total acidity (g/L) ratio

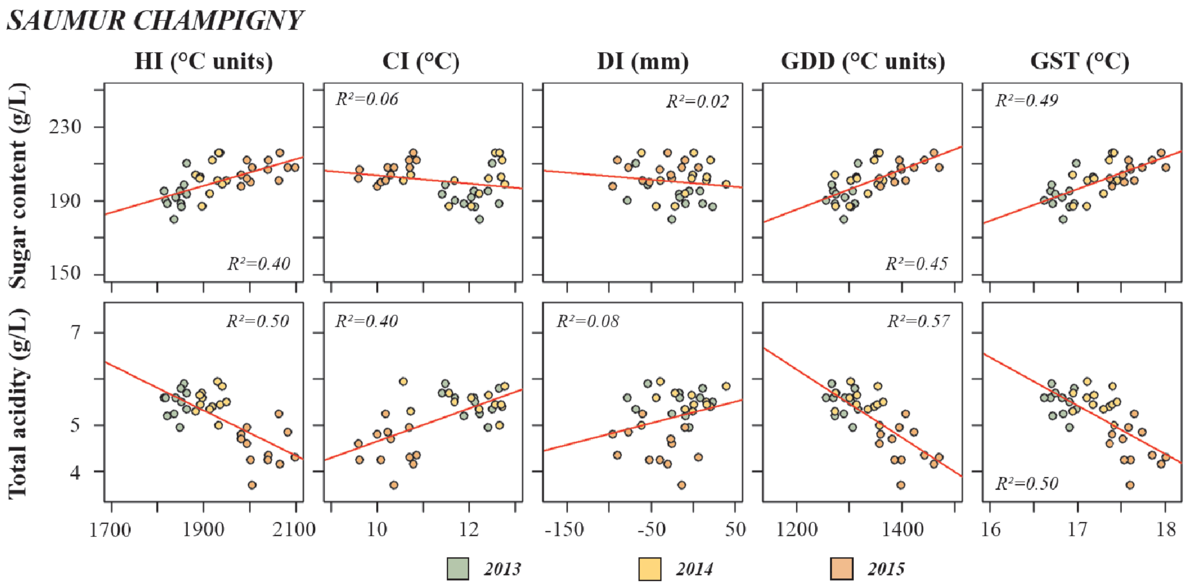

Figure 2. Linear relationships between the sugar content (g/L) and total acidity (g/L) five weeks post-véraison (mean date for all vineyard plots) and the values of the studied bioclimatic indices (HI, CI, DI, GDD and GST) from, 2013 to, 2015 for the AOP Saumur Champigny (variety Cabernet franc). The corresponding coefficient of determination, R^2, for each linear model is shown.

4. Local climate vulnerability and winegrowers adaptive processes

There was good consistency among winegrowers as they described wine quality. Indeed, winegrowers showed great capacity to recall detailed descriptions of wine quality and these detailed descriptions structured their perceptions of climate characteristics during past growing seasons. As they differentiated between favorable and unfavorable climate conditions, three variables emerged as the most significant: the amount of heat units, the seasonal amount and timing of rainfall, and the incidence of late spring frosts. As winegrowers described in detail the influence of these three variables, climate-related exposure and sensitivity appeared to be dependent on many contextual factors interacting with the regional oceanic climate (Neethling *et al.*, 2016).

In response to climate- and non-climate-related variables, important changes in viticultural practices occurred for both study areas over recent decades. Winegrowers identified the 1990s as a ‘turning point’ for practices due to the high quality seasons of 1989 and 1990, followed by the very poor seasons of 1991 and 1992. With the aim of producing quality wines consistently and not only under favorable climate conditions, winegrowers understood that they had to reconsider their viticultural practices in order to better manage climate-related risks and opportunities. Among those practices, vine inter-row management practices changed the most significantly for all winegrowers, being the most dynamic practice, changing at different temporal and spatial scales in response to many climate- and non-climate-related variables.

Winegrowers identified most adaptive responses to occur during harvest or winemaking, such as blending wines from different vineyards to maintain quality. Still, the impacts of climate variations are not new and adapting to those conditions has always been a constant challenge faced by winegrowers. Winegrowers underlined that through various learning experiences, shared knowledge (i.e., practical and scientific) and changing viticultural practices, they enhance their adaptive responses.

As was the case with studies conducted in Europe and France (Battaglini *et al.*, 2009; Rochard *et al.*, 2010), winegrowers observed regional climate changes and their impacts on vine phenology and grape quality. Recent climate changes were identified as having been favorable for grapevine behavior, with positive impacts on overall grape and wine quality. Winegrowers were nevertheless careful not to identify climate change as the main causal factor, stressing that their evolving viticultural practices have played a significant role in improving grapevine behavior and wine quality. Concerning the persistence and future direction of regional climate changes, all winegrowers described a great uncertainty. They perceive climate conditions to be more dependent on natural variability, i.e., variations

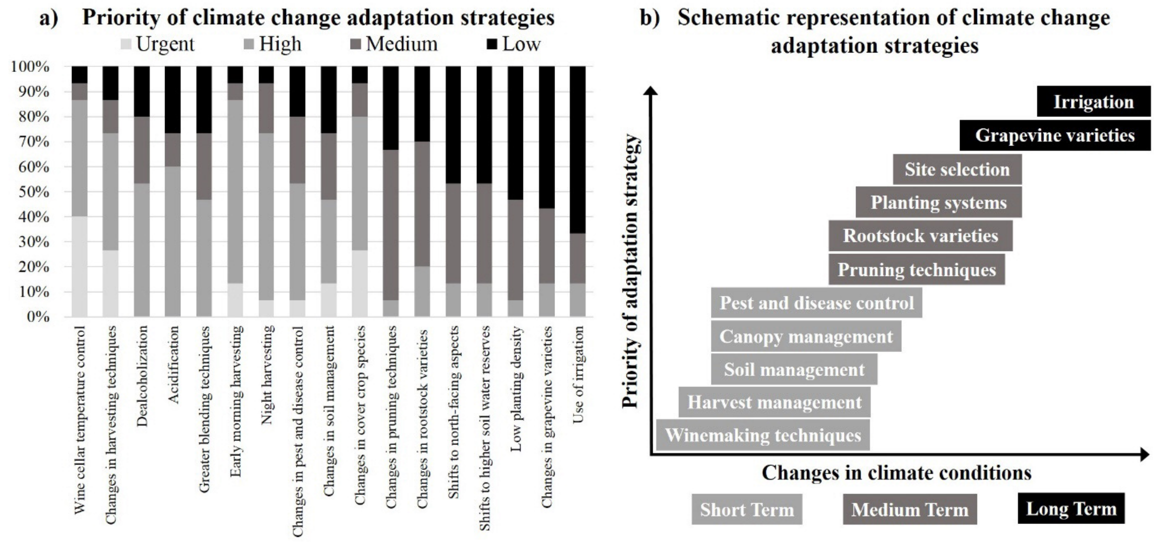

Figure 3. Priority of climate change adaptation strategies (a.) and schematic representation in the short, medium and long term over the 21st century (b.) based on the responses of winegrowers from Saumur Champigny.

between cold and wet periods as in the 1960s to 1970s, followed by warm and dry periods since 1990. Winegrowers' uncertainties about future climate changes were reflected in their outlook on adaptation priorities over the twenty-first century. Figure 3 shows the example of Saumur Champigny. Winegrowers placed the highest priority on annual practices, while changing grapevine varieties and using irrigation for vine water supply received the lowest priority.

Conclusion

This study was conducted in two regulated wine producing areas in the Anjou-Saumur wine growing sub-region, France. In the context of assessing climate change adaptation, a local-based approach was used to first study the spatial variability in climate and grapevine behavior. At local terroir scales, study results have revealed a strong spatial variability in temperature variables and bioclimatic indices within the vineyards of the AOP Coteaux du Layon and AOP Saumur Champigny. Overall, the local climate variability was related to grapevine growth and berry composition. Vineyard plots with greater heat accumulation had earlier phenological stages and higher maturity indices. These results illustrate that adaptation solutions to climate change do exist at local scales. This spatial heterogeneity in environmental conditions should represent an important buffer in response to future climate changes, allowing wine growing to manage the rapid changes expected in wine quality and typicity. Over the short and medium term, or based on the outcomes of lower- and intermediate-level emission scenarios, this spatial heterogeneity should further permit winegrowers to maintain current grapevine varieties and remain within the traditional boundaries of wine producing areas.

The local-based approach used in this study also led to the evaluation of winegrowers' decision-making processes and management practices. With a focus on wine quality, study findings have shown that in addition to the regional prevailing climate, local environmental features and socio-economic aspects are key determining factors of exposure and sensitivity. As each wine growing region consists of unique contexts, knowledge and understanding of those contextual factors, and their interaction with the regional climate, will be essential for winegrowers to identify and prioritize adaptation initiatives. Indeed, dealing with current exposure and sensitivity constitutes a first step towards adapting to future vulnerability and long-term climate changes. Through constant learning experiences and a range of management practices, study findings have also shown that winegrowers' decision-making is an on-going process, depending on many climate- and non-climate-related factors. Local assessment approaches are therefore essential to outline those deciding factors that assist or constrain the process of autonomous adaptations. Within the context of climate change and the key issues surrounding adaptation, these results highlight the importance of local, contextual knowledge in framing vulnerability and understanding its differences across and within wine growing regions.

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Grapevine genetics and climate change

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Abstract

Climate change is modifying the environmental conditions in all the vineyards across the world. The expected effects on grape and wine production can be positive in some grape growing regions, but under warmer or drier conditions the volume and quality of the wines produced can be decreased. Adaptation to new climatic conditions may include changes in the cultivation areas, changes in the vineyard or cellar practices, or use of new rootstock × scion combinations. The present article provides an overview of the possible effects of climate change on grapevine physiology and berry quality and describes the more important traits and the genetic variability that can be used in the adaptation process. We also present the modern techniques that can be used by researchers to identify the links between genomic information and plant performances in the field. Finally, we discuss on the existing opportunities in the present grapevine collections and on the strategies that can be used by breeders to create new varieties.

Keywords: grapevine, climate change, adaptation, genetic variability

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Introduction

There is no doubt that climatic conditions have changed all around the world during the past decades, and simulations with different scenarios of greenhouse gas emissions (GHG) show that the observed tendencies will continue during the present century (IPCC, 2014). Agricultural production in general is very responsive to environmental conditions. Destabilization of grape and wine production due to climate change can have not only significant direct impacts on farmers' incomes (Moriondo *et al.*, 2011) and employment in the wine industry, but also indirect impacts on land use, landscapes, tourism activities and rural life in numerous regions.

Because CO_2 is the elementary molecule at the origin of plant biomass, the expected increase in atmospheric CO_2 concentration can have direct effects on the physiology of the plants. However, the most studied effects of this increase are the possible impacts on climatic conditions. The Intergovernmental Panel on Climate Change (IPCC) forecasts an increase of temperatures across the globe (IPCC, 2014) and changes in precipitations, with more contrasts between wet and dry areas and wet and dry seasons, and more extreme precipitation events (IPCC, 2014). The last IPCC report predicts specific regional changes but does not confirm a general tendency of increased drought risks.

Adaptation of the grape and wine industry to climatic changes can be envisaged at different geographical scales, by moving cultivation areas, at different time scales or by changing the profiles of the wines produced. Here, we will consider that a successful adaptation to climate change is one that allows maintaining the same volume and quality of wine for a given area in the future.

This goal can be achieved by changes in the vineyard or cellar practices or by local adjustments of the location of the vineyards using the existing small-scale variability (Bonnefoy *et al.*, 2013). Here, we will focus on how grapevine genetics can help in the adaptation process.

Before describing the genetic variability and how it can be used, an overview of the expected impact of climatic change on grapevine is necessary.

Expected effects of climate change

1. A shift in developmental stages

The first effect of climatic change is an advance of developmental stages, observed worldwide (Duchêne and Schneider, 2005; Petrie and Sadras, 2008). The link between grapevine phenology and temperatures is so tight 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 (Duchêne *et al.*, 2010; Fila *et al.*, 2014). These models forecasted an advance of two to three weeks by 2050 when compared to the last 30 years (Duchêne *et al.*, 2010; Moriondo *et al.*, 2011).

As a consequence of earlier veraison dates, berry ripening will occur earlier in summer, under higher temperatures, and this can have a significant impact on berry quality.

2. Effects on grape and wine quality

High temperatures accelerate the decrease of grape acidity, mainly because of a faster degradation of malic acid (Kliewer, 1971; Sweetman *et al.*, 2014). Grapevine varieties containing high quantities of tartaric acid should be less sensitive to climate change because the quantity of tartaric acid per berry is stable during berry ripening (DeBolt *et al.*, 2008).

An increase of berry sugar content or alcohol concentration in wines during the past decades was frequently reported (Alston *et al.*, 2011; Duchêne and Schneider, 2005; Neethling *et al.*, 2012). Although the role of changes in management techniques can be discussed, early dates of veraison and better ripening conditions have a key role in this increase. Harvesting earlier is not an appropriate solution because grapes would not have the correct phenolic maturity (Palliotti *et al.*, 2013; Sadras and Moran, 2012).

High temperatures also impair the accumulation of anthocyanins in the berries (Mori *et al.*, 2007), but increasing radiation can have opposite effects (Teixeira *et al.*, 2013). There are indirect results showing that increasing temperatures are generally unfavorable to wine quality (Jones *et al.*, 2005; Moriondo *et al.*, 2011; Tonietto and Carbonneau, 2004), but, until now, there are no convincing data on the effects of high temperatures on aroma compounds. Bureau *et al.* (2000) studied the effects of the light environment on aroma compounds by comparing bunches exposed to the sun, bunches shaded by leaves and bunches shaded by black cloths. They quantified molecules of the terpenol family that participate in muscat-like aromas. The highest terpenol content was observed in the naturally shaded bunches and the lowest terpenol content in the artificially shaded bunches. The authors suggested that these differences could be related to a modification of the red/far red radiation ratio and/or to the temperatures recorded around the bunches.

Climate change is, first of all, the result of an increase of atmospheric CO_2 concentrations. In FACE experiments, elevated CO_2 concentrations had few effects on the concentrations of primary metabolites of the berries, i.e. sugars and acids (Bindi *et al.*, 2001; Gonçalves *et al.*, 2009). However, Gonçalves *et al.* (2009) showed that elevated CO_2 concentrations can modify the profile of secondary metabolites in wines.

3. Uncertainties about yield

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 biomass production (Bindi *et al.*, 2001; Garcia de Cortazar Atauri, 2006; Moutinho-Pereira *et al.*, 2009). However, the increase in total biomass expected in the future might be limited by rainfall distribution and water availability, especially at the end of the growth cycle (Garcia de Cortazar Atauri, 2006). The effects of climate change on fruit biomass, i.e. yield, are more difficult to anticipate. With mechanistic models, conclusions tightly depend on the regions studied (Garcia de Cortazar Atauri, 2006) and on the climatic datasets used (Bindi *et al.*, 1996). The overall tendency in the South of France and in Italy is a decrease in yield potential in the future (Bindi *et al.*, 1996; Garcia de Cortazar Atauri, 2006; Moriondo *et al.*, 2011).

The number of flowers determines an upper limit for the final number of berries per plant or per m^2 (Duchêne *et al.*, 2001). This variable depends, on the one hand, on the number of flowers per inflorescence and, on the other hand, on the number of inflorescences per shoot. 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). Frost damage around budburst can also reduce the number of inflorescences, but Molitor *et al.* (2014) demonstrated that, in Luxembourg, the risk of frost around budburst should decrease in the future.

High temperatures and high light intensity during the floral initiation process can increase the number of inflorescences (Buttrose, 1970), but a water deficit during this period can have strong opposite effects (Buttrose, 1974; Matthews and Anderson, 1989). Water deficits also negatively affect berry weight, especially when applied before veraison (Intrigliolo *et al.*, 2012). In addition to the effect of water deficit, Guilpart *et al.* (2014) showed that nitrogen availability around flowering is also a driver of grape fertility in the following growing season. It is possible that decreasing soil humidity due to climatic change can reduce soil nitrogen mineralization, and consequently indirectly affects bud fertility.

The role of atmospheric CO_2 concentrations on flower number has not been investigated yet. It is likely to be positive because bud fertility increases with vine vigor (Huglin and Schneider, 1998), which is higher under elevated atmospheric CO_2 concentrations (Bindi *et al.*, 2001).

It is difficult to forecast the consequences of climate change on grape yields because of the numerous yield components and climatic factors involved, including CO_2 concentrations. However, the main risk, arising more from experts assessment than from crop modeling (Pieri and Lebon, 2014), is that yields will be limited by water availability, especially in summer.

The frequency of extreme events (heat waves, heavy precipitations) is expected to increase with increasing global temperature (IPCC, 2014). This qualitative information is difficult to integrate in an adaptive approach, but it is necessary to keep it in mind.

Several authors have attempted to predict the evolution of pests and diseases in the future. The tolerance/resistance of grapevine varieties to pests and diseases will not be discussed here.

How to use the genetic variability?

Thanks to the use of molecular markers, the history of grapevine evolution is now well described (Bacilieri *et al.*, 2013). In this respect, 12,314 different accessions of *Vitis vinifera* are referenced in the Vitis International Variety Catalogue (http://www.vivc.de, February 2016). They result from two main sources of genetic variation: mutations and sexual reproduction.

Grapevine plants are reproduced by vegetative propagation. New features can appear spontaneously in a bud after accidental modifications in the DNA, which is the physical support of genetic information, during the process of cell division. These modifications include single base mutations (Single Nucleotide Polymorphism, SNP), insertion or deletion of small DNA fragments, and insertion of transposable elements (large DNA fragments). These natural and spontaneous events do not always induce visible effects, but when they do, the new plant can bear interesting traits: white color, muscat-like aroma or erect habit for example. This emergence of genetic variability is still going on and leads to «clonal variation»: within a variety, slightly different plants can be identified and their characteristics can be transmitted by vegetative propagation. The mutations sometimes affect only some of the cell layers of plant tissues, creating what is called «chimeras». Pinot gris (Hocquigny *et al.*, 2004) and Pinot meunier (Franks *et al.*, 2002) are examples of chimeric grapevine genotypes.

The existing clone collections can be explored to detect any phenotypic variation that could be useful in adaptation to climate change.

The other major source of genetic and phenotypic variation is sexual reproduction. Many famous cultivars such as Cabernet-Sauvignon (Bowers and Meredith, 1997), Chardonnay (Bowers *et al.*, 1999) or Merlot (Boursiquot *et al.*, 2009) are descendants of other known varieties. Sexual reproduction, due to chance or directed by man, is a major driver of genetic diversity in cultivated grapevine.

Researchers use different methods to detect the relationships between the genetic information on chromosomes and the features of grapevine plants. The first one is based on the generation of genetic variations through sexual reproduction: crossing two parents, chosen for some traits of interest, creates hundreds of individuals. The variation in genetic information among all the individuals of the progeny is revealed by the use of molecular markers. The number of molecular markers can vary from 100-200 to thousands with modern techniques (Barba *et al.*, 2014). In parallel, some traits of agronomical or enological interest are measured on the same plants and statistical methods are used to detect the relationships between the presence of some alleles at a precise locus on the genome and the trait of interest. When allelic variation in a chromosomal region correlates with variation of a trait of interest, this region is described as a «Quantitative Trait Locus» or QTL.

QTL detection has been extensively used in grapevine (review by Martinez-Zapater *et al.*, 2010). The availability of the grapevine whole genome sequence (Jaillon *et al.*, 2007) is very useful for identifying the genes involved in the variations of the trait of interest.

Another method is to characterize the genome and a trait of interest for a large population of unrelated grapevine genotypes. The basic idea is the same as for QTL detection: finding associations between DNA information and the values of a trait of interest. This method, named «Genome Wide Association», has been successfully used for the detection of alleles linked to the aroma (Emanuelli *et al.*, 2010) or anthocyanin content in grapevine berries (Fournier-Level *et al.*, 2009).

Once a strong link is found between a variation in the DNA and a variation in a trait of interest (even if it is only statistical), breeders can use this knowledge for creating new grapevine varieties efficiently. Molecular markers are used to select the plantlets bearing the desired alleles. The number of molecular markers used will depend on the number of traits under selection and the genetic architecture of the trait. For example, for selecting a genotype with a muscat-like aroma (high linalool content), two specific alleles, one from chromosome 5 and one from chromosome 10, are necessary (Duchêne *et al.*, 2009; Duchêne *et al.*, 2012a).

Currently, QTLs and markers related to disease resistance are routinely used in Marker-Assisted Selection (MAS) programs (Eibach *et al.*, 2007).

Breeding programs are currently more oriented towards tolerance to disease than adaptation to climate change. There is, however, increasing information on the genetic determinism of traits playing a role in adaptation to climate change.

Genetic variability for adaptation to climate change

In addition to changing cultivation zones and training systems, using different or even new genotypes, for both scion and rootstock, is a potentially powerful means of adaptation. Finding scion × rootstock × training system combinations able to produce commercial quality wine is a reasonable goal in many grape growing areas. It is, however, difficult to guarantee that the volume of production will be the same as today.

1. Phenology

The first intuitive idea is to use clones or varieties ripening later than the ones currently used. The variability for flowering and veraison time among existing genotypes is well described (Parker *et al.*, 2013), and models are able to predict the developmental stages in the future using climatic data (see Fila *et al.*, 2014 for example). Numerous QTLs for phenology have been identified (Costantini *et al.*, 2008; Duchêne *et al.*, 2012b; Fechter *et al.*, 2014; Grzeskowiak *et al.*, 2013), and this information can be used to test the adaptation of virtual genotypes in different grape growing areas for the future. However, we have shown that it is likely impossible in the future, even with late ripening varieties, to encounter the same cool ripening conditions that we experience today (Duchêne *et al.*, 2010). Indeed, there is a continuously increasing gap between a «cool ripening period», shifting later and later in fall, and the onset of ripening, moving towards the warmest period of summer. This analysis does not apply when ripening starts before the peak of high temperatures in summer. We should pay as much attention to the ability of genotypes to maintain some required characteristics under warm conditions as to phenological stages.

2. Water use

The crop water use efficiency (WUE) is a key parameter of adaptation to the expected drier summers in the future. There are many ways to define this parameter (see Flexas *et al.*, 2010 for a review). From a practical point of view, which can be the one of vine growers, it is the amount of water needed to produce one kilogram of mature grapes.

Many studies have compared the behaviors of different grapevine genotypes under water restriction, and classifications have been proposed (Bota *et al.*, 2001; Gaudillère *et al.*, 2002; Tomás *et al.*, 2014). The understanding of the genetic determinism of traits relevant for water stress tolerance is, however, still in its infancy, the first difficulty being to choose a relevant trait to study.

Classification into isohydric or anisohydric behavior is one of the methods proposed for describing cultivar response under water restriction. Isohydric cultivars are characterized by a high capacity to maintain high leaf water potential during the day, while the leaf water potential of anisohydric cultivars in the same conditions will drop significantly. The genetic basis for this trait was recently studied through a QTL approach on 186 genotypes (Figure 1), obtained from a reciprocal cross between Syrah and Grenache (Coupel-Ledru *et al.*, 2014).

The authors identified many QTLs for traits such as specific transpiration rate, specific hydraulic conductance or minimal daytime leaf water potential. Exploration of the correlations and co-localizations between QTLs of these traits suggested that (an)isohydry may be ruled by a dual control from hydraulic conductance and stomatal closure, rather than a unique role of the stomatal control of transpiration. Finding the best combination of alleles from different loci, leading to the optimal behavior under water restriction in the field, will require further progress in crop modeling (Tardieu, 2003).

There is also a large variability among rootstocks in water stress tolerance, from 110 R (tolerant) to Riparia Gloire de Montpellier (not tolerant) (reviewed by Serra *et al.*, 2014). Marguerit *et al.* (2012) have detected many QTLs related to transpiration rate, $\delta^{13}C$ values in leaves, transpiration efficiency and water extraction capacity by studying the responses of Cabernet-Sauvignon plants grafted on 138 genotypes from a Cabernet Sauvignon × *Vitis riparia* cv. Gloire de Montpellier cross (Figure 2). This study showed that scion transpiration rate and its acclimation to water deficit is controlled by the rootstock. Rootstocks can therefore also be bred to improve plant tolerance to water stress.

Berry quality

A high variability in berry sugar content can be found when comparing genotypes on the same date (Duchêne *et al.*, 2012c) or, conversely, on the date when the sugar content reaches a given value (Costantini *et al.*, 2008). However, these values depend, on the one hand, on the climatic conditions between veraison and harvest and, on the other hand, on the fruit to leaf ratio of the plants. It has been shown in a progeny from a Riesling × Gewurztraminer cross that when taking into account the genetic variability for veraison dates and fruit to leaf ratio, the residual genetic variability for sugar metabolism was low (Duchêne *et al.*, 2012c). Nevertheless, classical breeding has already created varieties with low sugar content producing wines with no more than 10-11% alcohol (Escudier, 2009). Possible driving factors can be high fruit to leaf ratio, late veraison dates or berry physiology. The actual genetic variability for sugar metabolism, and the underlying QTLs, remains to be explored.

Higher temperatures during ripening are responsible for a faster decrease of berry acidity, due to the degradation of malic acid (Sweetman *et al.*, 2014).

Tartaric acid concentration in berries is far less sensitive to high temperatures than malic acid concentration (Kliewer, 1971). Indeed, the quantity of tartaric acid per berry is generally constant throughout berry ripening (DeBolt *et al.*, 2008). Grapevine varieties with a high tartaric/malic ratio should be better adapted to warmer climatic conditions. As shown in Figure 3, there is genetic variability for the ratio between tartaric acid concentration and malic acid concentration in grapevine genotypes (Duchêne *et al.*, 2014). QTLs for pH and tartaric acid concentration have already been detected (Chen *et al.*, 2015), which opens the

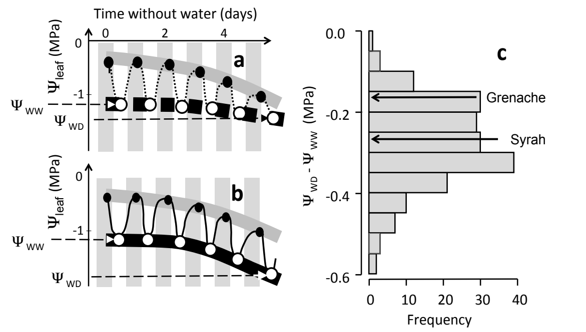

Figure 1. Schematic representation of the difference between isohydric (a) and anisohydric (b) response of leaf water potential (Ψ_{leaf}) to soil drying, and distribution of iso- to anisohydric responses observed within a Syrah × Grenache progeny composed of 186 offspring (c).

Experiment was performed on potted plants in a greenhouse where soil water potential (bold grey line and black points in a and b) was controlled to decrease to common target values in about 5 days for all plants. Ψ_{leaf} schematically oscillated each day between predawn values, in equilibrium with soil water potential (black points in a and b), and midday values (white points in a and b). The difference in midday Ψ_{leaf} between last day under water deficit conditions (Ψ_{WD}) and first day under well-watered conditions (Ψ_{WW}) characterizes the degree of iso- or anisohydry reported in c (Coupel-Ledru *et al.*, 2014).

gate for breeding varieties able to keep a correct level of acidity in the warm conditions of the future.

Regarding secondary metabolites, the decrease in anthocyanin content under high temperatures certainly differs among varieties (Kliewer and Torres, 1972). Understanding the genetic variability responsible for the profiles of phenolic compounds (Fournier-Level *et al.*, 2009; Huang *et al.*, 2012) can be of great help to breed new varieties whose color would be less affected by high temperatures. Up to now, there is no information on the possible different reactions of aromatic varieties to high temperatures.

Conclusion

Climate change will significantly modify the environmental conditions in most, if not all, vineyards in the world. The impacts on wine production will depend on the region and on the type of wine produced, but they will not always be negative: a warmer climate is a guarantee of ripe-harvested grapes every year and it will offer new opportunities for some currently cool grape growing regions.

The main risks are, on the one hand, a decrease of yields due to water scarcity and, on the other hand, the production of unbalanced wines with high alcohol content and low acidity. The consequences of new climatic conditions on the final concentrations of secondary metabolites (phenolic compounds, aromas) in wines are uneasy to anticipate. For anthocyanins for example, the positive effects of increasing solar radiation can, at least partly, counterbalance the negative effects of increasing temperatures in temperate climates. The possibility to delay harvest dates can also compensate for a lack of anthocyanin synthesis. Because grape anthocyanins will be impacted by concomitant variations of several factors, the final concentrations at harvest in future conditions are very difficult to predict. If vine growers are able to better control the sugar content and the acidity of the grapes in the future, they will have more degrees of freedom for choosing the harvest date when the balance between sugars, acidity and aromas or anthocyanins is optimal.

Vineyard management techniques and cellar practices can be modified in the short term. New training systems need to be developed and experimented first, and could be implemented in the middle term.

Adaptation of plant material can take place at several levels. Clone collections already exist and finding new clones for a given variety with higher acidity or lower sugar content can be achieved quite rapidly. A good point for clonal selection is that new clones can be cultivated without modifications of the regulation rules in the existing grape growing regions, including

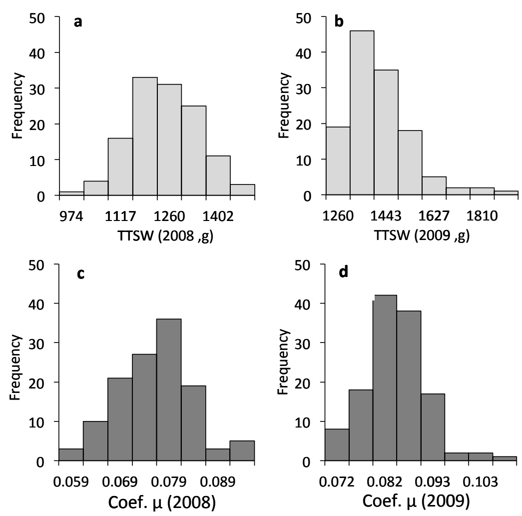

Figure 2. Phenotypic distributions of the traits of interest of the mapping population CS×RGM1995-1: total transpirable soil water (TTSW) in (a) 2008 and (b) 2009; coefficient µ of the normalised transpiration rate response curve to the fraction of transpirable soil water (FTSW) equation in (c) 2008 and (d) 2009 (from Marguerit *et al.*, 2012).

European vineyards under registered designations of origin. The weak point is that the extent of genetic variability found in these collections might be too restricted to meet a combination of expectations in terms of quality and yield. In other words, the existing clonal variability can be useful in the short term, possibly in the middle term, but certainly not in the long term.

The next strategy is to test already existing varieties. Grapevine is already cultivated in warm regions and there are thousands of cultivars available in the genetic resources collections around the world. Except for grape growing regions already at the warm limit of the grape cultivation area, it should be possible to find scion × rootstock combinations able to grow in most of the present grape growing regions. Finding the appropriate combination from both an agronomical and enological point of view is, however, a goal for the middle term. The acceptance of new varieties will be all the more easy as the typicity of wines will be preserved.

In the long term, the ultimate goal is to breed new varieties. This can be necessary if no scion × rootstock combination gives satisfactory agronomical results or if the requirements for wine typicity are not met. We have increasing knowledge on the genetic determinism of traits related to phenology, water use and berry quality, but we are still lacking ideotypes. In other words, the objectives for breeders are not straightforward. Even with efficient breeding techniques, it takes about 10 years between obtaining a seed and releasing a variety, and even longer for this variety to be cultivated on significant areas. Certainly for the first time in the history of breeding, the environmental conditions can change between the

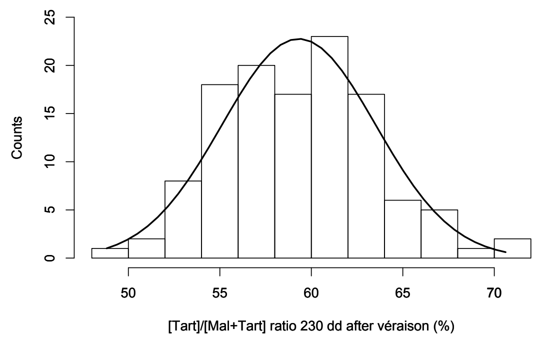

Figure 3. Variability of the ratio between tartaric acid concentration and the sum of malic and tartaric acid concentrations in progeny from a Riesling × Gewurztraminer cross (120 genotypes). Means of data from 2006 to 2009. Organic acid concentrations were measured 230 degree-days (dd) after veraison for each genotype in the INRA experimental vineyard in Bergheim (Duchêne *et al.*, 2014).

time varieties are evaluated and the time wine growers use them. There is a need to anticipate the behavior of genotypes in new environmental conditions. This requires not only reliable models for predicting future climatic conditions but also crop models able to integrate allelic variations and responses to environmental data. Using such models, breeders would be able to identify the best allele combination for a given set of climatic conditions before starting a breeding program using all modern techniques for revealing the genetic information in progenies.

Climate change is likely to modify wine production in many parts of the world. As of today, grapevine genetic diversity allows grapevine cultivation and wine production in a wide range of environmental conditions across the world. In the future, the existing variability can be used, or extended by sexual reproduction, to provide solutions for adapting grapevine production to climate change.

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Developmental, molecular and genetic studies on grapevine response to temperature open breeding strategies for adaptation to warming

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Abstract

Aim: In the long term, genetic improvement is one of the major strategies to support sustainable wine production in a changing climate. Over the past 5 years, we have developed an interdisciplinary research program that aimed to: i) characterize the impact of temperature increase sensed by the entire plant or individual bunches on the development and functioning of the plant, ii) identify the physiological and molecular mechanisms regulating the response of vegetative and reproductive development to heat stress and iii) develop tools to map quantitative trait loci (QTLs) of plant and berry development in duly controlled, stable, and contrasting environmental conditions.

Methods and results: Performing high-throughput genomic analyses combined with the use of innovative experimental designs (fruiting cuttings, microvines, single berry sampling) was critical to decipher the ecophysiological and molecular mechanisms involved in the vine response to high temperature.

Conclusion: Warming promotes vegetative growth and hampers plant carbon balance, disturbing flower set and young berry development. High temperatures modify primary and secondary fruit metabolisms, desynchronizing sugar and organic acid metabolisms and delaying sugar and polyphenol accumulation during ripening. The study of day and night transcriptomic and proteomic signatures associated with heat highlighted key players of the response to temperature in the fruit.

Significance and impact of the study: Capitalizing on this knowledge, a new program is being proposed for the selection of cultivars limiting the accumulation of sugars in the berry while maintaining other qualitative compounds.

Keywords: Global warming, temperature, grapevine, biology, adaptation, genetic improvement

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Introduction

Grapevine performance, including productivity and wine quality, is highly dependent on climate. High temperatures (T°) hamper carbon assimilation beyond a 30 °C threshold (Greer and Weedon, 2012) and limit the yield by reducing the number of berries per vine (Rogiers *et al.*, 2011). The composition of the wines also depends on thermal conditions (Spayd *et al.*, 2002; Carbonneau *et al.*, 2015) because T° increases sugar concentration in the berry at the expense of malic acid and secondary metabolites, leading to unbalanced wines.

In Europe, wine production relies on close interactions between the variety, the environment and the viticultural practices. Climate change disrupts this balance; hence varietal adaptation is required to maintain traditional and qualitative viticulture in these regions (Torregrosa *et al.*, 2011; Ollat *et al.*, 2014 and 2015). In the long term, genetic improvement is one of the best strategies to support sustainable wine production systems under global warming. Various data confirm that genetic diversity within *Vitis* may be exploited for photosynthesis adaptation to temperature. For example, photosynthesis was not reduced at T°<40 °C in response to heat stress treatments in *V. amurensis* (Luo *et al.*, 2011), and most wild species and hybrids between *V. labrusca* and *V. vinifera* also displayed a better heat tolerance than *V. vinifera* (Xu *et al.*, 2014). Recently, Hochberg *et al.* (2015) observed metabolic adaptations resulting in greater growth inhibition of leaves at 35 °C for cv. Syrah compared to Cabernet Sauvignon. Unfortunately, the lack of physiological and genetic knowledge on the mechanisms of adaptation of grapevine to T° limits the development of non-empirical breeding programs (Torregrosa *et al.*, 2011), insofar as fruit quality, rather than carbon fixation, is considered as the principal selection target. In the last years, much effort has been carried out under vineyard conditions to identify regulatory mechanisms of primary and secondary metabolisms in berries (Deluc *et al.*, 2008; Boss and Davies, 2009; Hichri *et al.*, 2011; Lecourieux *et al.*, 2014) and to identify transcriptomic changes induced by thermal stress applied to the berry (Pillet *et al.*, 2012) or to the whole plant (Carbonell-Bejerano *et al.*, 2013; Rienth *et al.*, 2014b; Rienth *et al.*, 2016).

Despite these recent successes, we are far from a comprehensive picture of the regulatory mechanisms involved in the adaptation of the grape to heat stress. To date, there is no genetic tool or resource suitable to support breeding programs dealing with T° resilience. Over the last 5 years, we have developed a research program aiming to: i) characterize the effects of T° increase, applied at the whole plant or fruit level, on the development and functioning of the plant (organogenesis, biomass partitioning, metabolism of the berry), ii) identify the specific roles of carbon balance and molecular (transcription) mechanisms in regulating yield and quality development under high T° and iii) develop resources to study the genetic structure and stability of developmental and qualitative berry characters against thermal fluctuations.

As with other perennial plants, the biological properties of grapevine cause methodological and experimental difficulties for studying the response to environmental changes and genetic diversity. Indeed, its size, its long juvenile period and its discontinuous reproductive cycle lengthen and complicate the study of such issues. Therefore, this project relied on two alternative models: the microvine (Chaib *et al.*, 2010; Rienth *et al.*, 2012; Torregrosa *et al.*, 2016), which presents a dwarf stature and continuous fruiting, and fruiting cuttings (Mullins, 1966), which allow to get grapes in the off-season and grow them under strictly controlled conditions (Luchaire *et al.*, 2013; Rienth *et al.*, 2013).

This work reveals the central role of carbon balance in the plant response to thermal stress, with critical effects on the distribution of biomass within the plant and also changes in the primary (sugars, organic acids) and secondary (phenolic compounds) berry metabolism. This work also highlights day and night transcriptomic and proteomic signatures associated with heat stresses in grapes. During the program, new tools have been developed for grapevine phenotyping and breeding. The most significant were: i) a spatio-temporal analysis framework of microvine vegetative and reproductive development, ii) stable quantitative trait loci (QTLs) of development *vs* T° and iii) methodologies for RNA purification, proline quantification assays and microvine embryo rescue.

Materials and methods

1. Vine responses to T° applied at whole plant

Temperature effects on biomass partitioning between vegetative and reproductive organs and on carbon balance in microvine

Six experiments (Exp.1 to 6) were performed on two-year-old own-rooted potted microvines (line ML1, Chaïb *et al.*, 2010). Plants (6 to 12 per experiment) were thinned to one main axis and laterals were removed as soon as they appeared. Irrigation was supplied to fit maximal evapotranspiration. In Exp. 1

to 2 (2011) and Exp. 3 to 5 (2013), contrasted temperature treatments were applied over a 1- to 2-month period after the first inflorescences started to ripe. Control day/night air T° was set to 25 °C/15 °C. Contrasted T° were applied both above and below control T°, ranging from 22 °C/12 °C in Exp. 1 to 30 °C/20 °C in Exp. 2, 30 °C/15 °C in Exp. 4 and 30 °C/25 °C in Exp. 5. In Exp. 6, several couples of day/night T° from 20 °C/15 °C to 35 °C/30 °C were applied for 2 days. In all experiments, a 14-h photoperiod was imposed to reach a daily PAR (photosynthetically active radiation) close to 19.0 mol $m^{-2}d^{-1}$. The daily mean VPD (vapor pressure deficit) was maintained close to 1 kPa in Exp. 1 to 5 and close to 2 kPa in Exp. 6.

Spatial changes in biomass partitioning in above-ground organs

The number of unfolded leaves and the rank of the most apical phytomer at flowering (50 % of opened flowers) were recorded for Exp. 1 to 5 at the beginning of the experiment. Three plants were harvested at T0 for Exp. 3 to 5. Berries, leaves and internodes were then harvested and weighed (dry matter) to determine the biomass gain between T0 and final harvest.

Whole plant gas exchange measurements

Exp. 6 was dedicated to whole plant gas exchange measurement. As described in Bédiée *et al.* (2015), net photosynthesis and respiration of whole aerial organs were recorded for 24 h on 3 plants at several day/night T° couples.

Biochemical/transcriptomic berry responses

In order to study the T° effects on microvine fruit development, additional experiments were added to those described above. A first monitoring of microvine fruit development was conducted at 30 °C/20 °C (day/night T°). Biochemical and transcriptomic signatures were studied at day- and nighttime as described in Rienth *et al.* (2014a). Subsequently, short heat stress experiments were conducted at 3 fruit development stages. Plants were acclimatized for 10 days at constant day/night T° (22 °C/12 °C), then heat stressed (37 °C) for 2 h (Rienth *et al.*, 2014b). Long-term T° effects on whole berry development were studied in Exp. 1 and 2. In Exp. 3 and 5, only the *véraison* and ripening stages were studied. The green growth stage of the berry was analyzed in Exp. 4 adding an additional experiment (Exp. 7) using 20 °C/15 °C (day/night T°).

For Exp. 1 and 2, all major biochemical compounds were analyzed during the whole fruit cycle without any transcriptomic characterization. For Exp. 3, 4, 5 and 7, berry RNA was extracted as described in Rienth *et al.* (2014c) and berry transcriptome was studied using a NimbleGen microarray 090818 Vitis exp HX12, which contains 29,549 predicted genes representing 98.6 % of the 12X grapevine gene prediction version V1, and RNA-seq using Illumina paired-end sequencing (Rienth *et al.*, 2016). For stages close to *véraison*, berries were sorted based on their individual sugar and acid composition, in order to homogenize the sampling for transcriptomics.

2. Fruit responses to T° applied at bunch level

To characterize the response of grape to micro-environmental thermal stress, experiments were conducted over 3 years with fruiting cuttings of Cabernet-Sauvignon. Cuttings were grown in small pots, with clusters exposed to an elevated temperature airflow produced by fan heaters (Figure 1). The other

Figure 1 - Experimental system used to investigate the effect of heat at the bunch level.
(a) Cabernet Sauvignon fruiting cuttings were used to expose clusters to an elevated T° airflow produced by fan heaters. (b) The other plant organs were all protected from the warmed airflow by polystyrene foam deflectors.

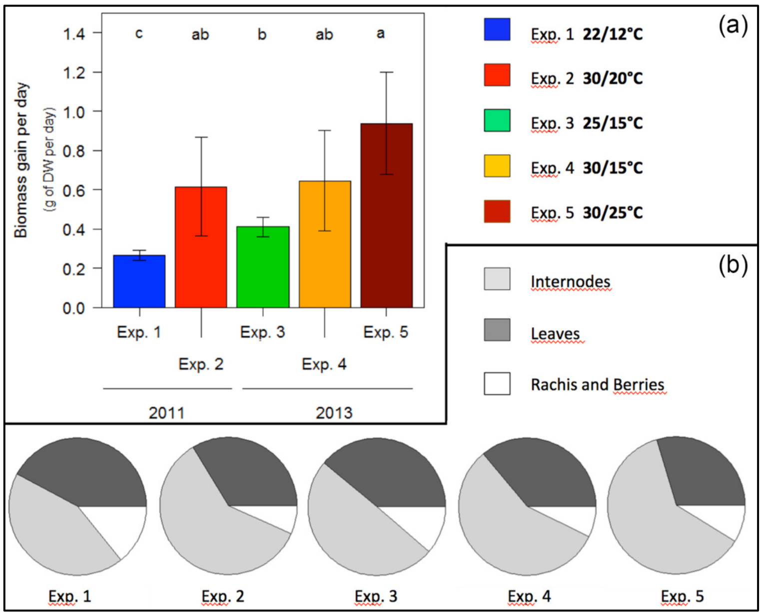

Figure 2 - Biomass gain during thermal experiments along the shoot expressed in g of DW per day (a) and in g per organ type (b). Only the phytomers that expanded during the T° treatment and the ones that had not reached the mid-flowering stage at T0 were considered. Each value is the average of 6-12 plants, depending on the experiment considered (bar corresponds to standard deviation).

plant organs were all protected from the warmed airflow by polystyrene deflectors. High T° was applied at 3 berry developmental stages (middle-green, *véraison*, and mid-ripening) and maintained daily (7:00 am to 7:00 pm) until harvesting. An average daytime fruit T° of 26 °C was set for the control and compared to a 34 °C "hot" treatment. This led to a mean T° difference of about 8 °C between heat stressed and control clusters, i. e. close to the range observed in vineyards between sun-exposed and shaded berries (Pieri and Fermaud, 2004). In order to analyze short- and long-term responses to T°, control and heat stressed berries were collected at 3 different time points (1, 7, and 14 days) and used for biochemical, transcriptomic and proteomic analyses. Transcriptomic analysis was performed using the NimbleGen microarray described above. The relative quantification of proteins was performed using a label-free LC-MS/MS-based shotgun proteomic approach.

3. Genetic mapping of developmental traits

Several crosses were performed between 2 microvine genotypes (ML1 and ML3, heterozygous *VvGAI1*/*Vvgai1* lines) and 4 *V. vinifera* cultivars (Alicante Bouschet, Muscat de Hambourg, Savagin, and Carignan). Crosses were performed to create several segregating progenies, as described in Chaïb *et al.* (2010). A mapping population of 129 microvines from the cross Picovine x Ugni Blanc *flb* (Fernandez *et al.*, 2013) was phenotyped for 43 traits in up to 9 environments (vegetative, reproductive and berry composition at both green lag phase and maturity), including an experiment in growth chambers with 2 contrasted day/night T° (30 °C/25 °C *vs* 20 °C/15 °C). This population was genotyped with a 18K SNP Illumina VeraCode chip (Le Paslier *et al.*, 2013), and 6000 informative SNPs (single-nucleotide polymorphisms) were used to build parental genetic maps with CarthaGene software (De Givry *et al.*, 2005). QTLs were detected in each environment with Rqtl (Broman *et al.*, 2003).

Results and discussion

1. At whole plant level, T° promotes biomass sequestration into the leaves and internodes at the expense of inflorescence rachis and berries

T° elevation significantly increased the above-ground biomass gain per day, specifically in vegetative organs (leaves and internodes; Figure 2a, 2b). In contrast, biomass allocation toward the rachis and the berries was reduced by high T° due to the abortion of inflorescences (data not shown).

As the phyllochron was similar for all experiments (data not shown), plants exposed to high T° developed faster on a calendar day basis. Surprisingly, leaf and internode growths as a function of growing degree days were also higher under warm T°, although they generally follow invariant patterns both in annual (Turc and Lecoeur, 1997; Granier and Tardieu, 1998) and perennial plants (Lebon *et al.*, 2004; Dambreville *et al.*, 2013). The inflorescence drop under warm T° likely resulted from the incapacity of the plant to accommodate for the boost in carbon demand. It was previously reported for other species that carbon acquisition is lower and biomass "diluted" when T° increases (Vasseur *et al.*, 2011). Elevated T° were also found to lower the carbon storage in woody reserves in grapevine, with negative impact on fruitfulness and berry composition (Sadras and Moran, 2013; Sadras *et al.*, 2013; Rogiers *et al.*, 2011).

2. At whole plant level, high T° negatively impact microvine daily carbon balance

Net photosynthesis was optimum between 25-30 °C and decreased beyond 30 °C (Figure 3a). Night respiration exponentially increased within the range 15-30 °C (Figure 3b). Such patterns were consistent with those generally reported for grapevine (Zufferey *et al.,* 2000; Huang *et al.*, 2005). Carbon gain thus tended to slightly decrease when T° were higher, specifically at night (Figure 3c). Berry ripening (monitored through sugar accumulation) was much more delayed under warm T° on a thermal time basis than in calendar scale (Figure 4a, 4b). Thus, in contrast with vegetative organogenesis, berry development is not linearly linked to thermal time. The impairment of sugar accumulation by high T° fits with previous observations showing that fleshly fruit berries are very sensitive to heat during ripening (Civello *et al.*, 1997; Greer and Weston, 2010).

Taken together, our results globally fit with some previous findings on grapevine response to elevated T° such as the maintenance of biomass accumulation in vegetative organs, the reduction of carbon storage toward woody reserves and the delay of ripening. Importantly, they showed that with continuous flowering and fruiting, microvine is a suitable model to study the fine tuning of the vegetative and reproductive developmental sequence under T° fluctuations.

3. Effect of T° applied at whole plant on biochemical/transcriptomic berry responses

The microvine made it possible, for the first time, to characterize fleshy fruit development simultaneously during day and night under completely controlled conditions using whole genome microarrays. Up to this point, circadian cycles had only been studied on non-perennial model plants such as Arabidopsis (Schaffer *et al.*, 2001). For 2 green and ripening stages, gene expression changes occurring along development as well as between day/night were

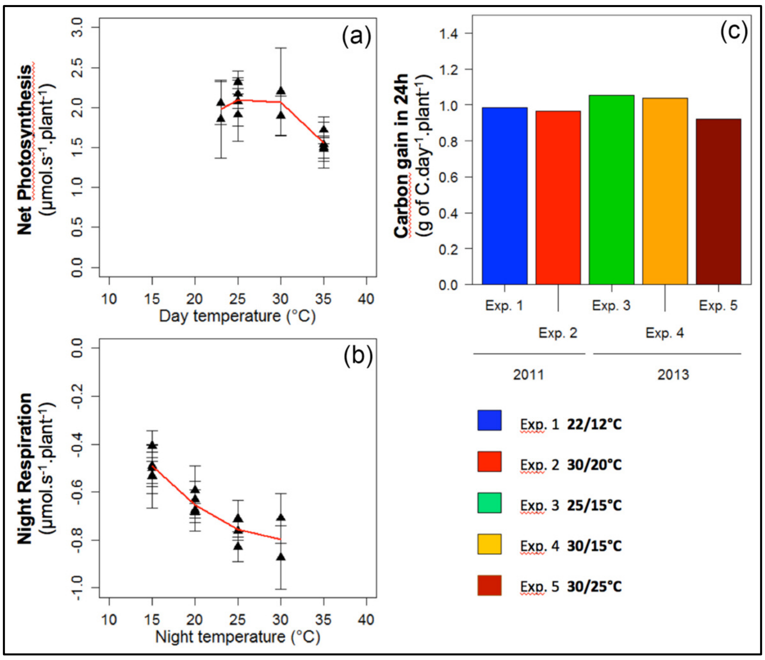

Figure 3 - Microvine whole plant (aerial organs only) net photosynthesis (a) and night respiration (b) responses to day T° and night T°, respectively. Each point is the average of 3 plants during one complete day or night measurement. Data were obtained during Exp. 6. Carbon gain over 24 h was calculated for the Exp. 1 to 5 thermal conditions (c). Carbon gain was estimated from photosynthesis and respiration response to T° fitting curves on (a) and (b).

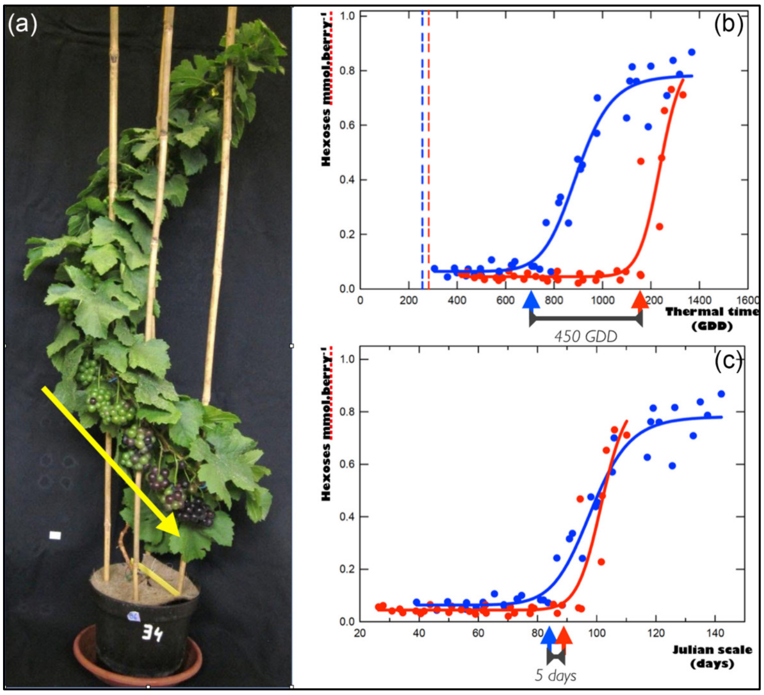

Figure 4 - Effect of +8 °C on the accumulation of sugars in the microvine berry.
(a) A ML1 microvine plant during the experiment.
Organs were spatially sampled and spatial positions converted using the phyllochron and the sum of T° above +10 °C. (b) The accumulation of sugars as a GDD (Growing degree days) function. (c). The accumulation of sugars as a calendar function.

studied. All day-detected developmentally regulated transcripts were also modulated at night, whereas, surprisingly, 1,843 supplementary genes displayed night-specific developmental regulation. Hierarchical clustering of those transcripts revealed a similar regulation pattern at day and night with secondary metabolism being more distinctly regulated during night development. A diurnal modulation throughout all stages could only be detected for 9 transcripts, indicating that circadian regulation in the berry has a high stage specificity. Regarding functional categories, mainly cellular organization and photosynthesis were day-upregulated in green berries, whereas secondary metabolism and stress-related genes were night-upregulated in ripening berries.

Short T° stresses confirmed that gene modulation could vary to a large extent according to sampling time. Application of a short stress at 3 different stages at day and night yielded a total of 5,653 modulated transcripts (two-fold change, $p<0.05$). Responsive pathways differed according to time and stage. A clear distinction of ripening stages by single berry selection led to stage-specific detection of malic acid metabolism-related transcripts displaying heat activation, whereas anthocyanin regulatory genes were repressed. Although stress application lasted only 2 h, a heat-induced delay in ripening and sugar accumulation could already be observed at *véraison* at a transcriptomic level. The heat activation of several candidate genes controlling the responses to T° in the berry, *VvGols1* (Galactinol Synthase 1) and *VvHsfA2* (Heat stress factor A2), could be confirmed (Pillet *et al.*, 2012). One complementary Heat Shock transcription Factor (HSF), *VvMbf1c*, previously described in Arabidopsis (Suzuki *et al.*, 2011), could also be identified in the grapevine berry.

In a series of long-term T° treatments using day and night sampling of single berries corresponding to green and ripening stages, a total of 674 millions sequenced reads yielded 10,788 differentially expressed transcripts in response to T°. Green berry development accelerated as evidenced by higher rates of organic acid accumulation and berry growth under higher T°. This could be confirmed when considering the transcriptional signatures of genes related to cell expansion. Transcripts related to tannin synthesis (CHS, PAL) and galloylation were found to be repressed by high T°. Surprisingly, the onset of malate breakdown was delayed to mid-ripening when plants were grown under cold conditions. This observation suggests that malate breakdown is not an intrinsic part of the *véraison* program. Whole plant carbon balance could be determinant for the trigger of malate breakdown, which was considered to be non-plastic. Several ATPases and malate transporters displayed development and T° dependent expression patterns, besides less marked but significant regulation of other genes in the malate pathway.

Heat responsive genes (HSPs, HSFs) detected in the short heat stress studies were also found modulated by long-term treatments. However, several of them showed a decreased T° response indicating their role in short-term adaptation to high T°. By contrast, other transcripts maintained a high expression level even during night sampling, when night T° was kept stable besides various T° conditions.

The single berry biochemistry analysis made prior to RNA extraction not only made it possible to reduce biases in transcriptomic results (Carbonell-Bejerano *et al.*, 2016), but also highlighted that the ripening program of single berries can be faster than for whole bunches.

4. At bunch level, T° also dramatically changes the developmental program of the berry

With fruiting cutting experiments, metabolites (sugars, acids, phenolic compounds, amino acids) were quantified. Critical changes were observed for malic acid, anthocyanins, flavonols and some amino acids including GABA. We also noticed that accumulation of sugars and phenolic compounds was postponed by 2 to 3 weeks by heat stress applied at green stage. Transcriptomic analyses identified more than 7,500 transcripts showing differential expression under heat stress. However, most of these responses were found to be stage-specific and only 38 genes exhibited the same deregulation across all conditions.

To understand the biological significance of the differentially expressed genes, a Genome Ontology (GO) category enrichment analysis was performed and revealed both similar and different T° effects according to the developmental stage and the stress kinetics. Several significantly affected functional categories were identified, among which "abiotic-heat stress", "secondary metabolism", "transport", and "signaling". Interestingly, the category "RNA-regulation of transcription" is also highlighted through many heat responsive genes encoding putative transcription factors or epigenetic regulators. Proteomic analyses identified around 2,000 non-redundant proteins. T° led to significant remodeling of the berry proteome with up to 556 deregulated proteins. However, these responses depended on both developmental stage and stress length. The GO category enrichment analyses indicated that the most affected processes belong to stress responses, protein metabolism, and primary and secondary metabolism. Interestingly, less than 20 % of these heat-deregulated proteins were also modulated at the transcriptional level. Taken together, these omics data contribute to explain the dramatic changes in metabolite contents observed in heat stressed berries and highlight the intrinsic capacity of this fleshly fruit to perceive heat stress and to build adaptive responses.

We initiated the functional characterization of some major candidates. Both *VvGols1* and *VvHsfA2* were found upregulated at the transcriptional level in berries under heat stress. *VvGols1* expression profile correlated positively with galactinol accumulation in heat stressed berries. Heterologous expression of *VvGols1* in *E. coli* showed that it encodes a functional galactinol synthase. Transient expression assays showed that the heat stress factor *VvHsfA2* transactivates the promoter of *VvGols1* in a heat stress dependent manner. The results also suggest that galactinol may play a signaling role in these responses (Pillet *et al.*, 2012). To extend this study, several transgenic grapevine material (microvine, hairy roots and embryonic cells) over- or under-expressing *VvHsfA2* and *VvGols1* were produced. The characterization of these transgenic lines is under progress (phenotyping, heat sensitivity, transcriptomic and metabolic modifications). The functional characterization of other heat stress responsive genes that potentially act as transcription factors (TF) or epigenetic regulators was also initiated.

5. Identification and genetic mapping of developmental traits

All traits phenotyped segregated in the Picovigne x Ugni Blanc *flb* population (Figure 5). New correlations were found between malate and total sugars at green lag phase, and between internode length and leaf area (Houel *et al.*, 2015). Broad-sense heritability was unexpectedly lower than 0.40, except for traits related to berries and acids. Dense and reliable genetic maps were built for both parents, with low inter-marker distances. Fourteen QTLs were detected in at least two environments, among which a novel QTL for berry size on chromosome 7, explaining up to 44 % of total variance. This QTL was co-localized with QTLs for the number of berries, clusters and seeds, as well as with QTLs for major berry acids at green lag phase. The dwarf stature of the microvine allowed a fine phenotyping for many traits in a T° range wider than in previously published studies. Quantifying acids at green lag phase allowed us to find the first berry acidity QTLs in a *Vitis vinifera* intra-specific cross, and particularly the first QTLs for tartaric acid. These QTLs were found under several environments and then offer opportunities for breeding.

Conclusions

1. On the development of new methods to study the abiotic stress effect

A robust analytical framework was developed to characterize the phenotype of the microvine, especially for inferring temporal data from spatial data (Torregrosa *et al.*, 2016). Thus, it becomes possible to reduce the calendar duration of the experiments to a few days or weeks and to study simultaneously various stages of reproductive development (Rienth *et al.*, 2012 ; Luchaire *et al.*, 2015).

2. On the central role of carbon in the response to T° fluctuation

Data revealed a relationship between the lower carbon balance within the plant and the abortion of reproductive organs (Luchaire, 2015). In calendar time, while berry development remains stable, T° boosts vegetative organogenesis disturbing source/sink balance. As a consequence, the differential response of reproductive *vs* vegetative system occurs at the expense of berry biomass allocation. Then, T° can change malic acid metabolism in relation to the accumulation of sugar (Rienth *et al.*, 2016, Romieu *et al.*, 2016) by acting on the energy status of the plant. This observation reveals a hitherto unsuspected phenomenon because it was considered a dogma for the vine berry that the decrease in malic acid was triggered at the start of sugar unloading (Carbonneau *et al.*, 2015). These observations provide a new perspective on the capacity of a plant, subjected to limiting carbon assimilation conditions and/or to changes in biomass allocation, to support fruit energy supply. However, these data acquired with the microvine should be validated on other genotypes.

3. On the identification of specific regulatory elements controlling fruit response to heat

Elevated T° applied at the level of the fruit or the entire plant delayed fruit ripening, including sugar and secondary metabolite accumulation. We have found specific regulatory mechanisms that are independent of the carbon status of the plant, showing the existence of a direct impact of T° on fruit behavior. Thus, several regulators, metabolic elements (e.g. *VvGols1*) or transcription factors (*VvMbf1* or *VvHsfA2*) were highlighted, opening new avenues for research.

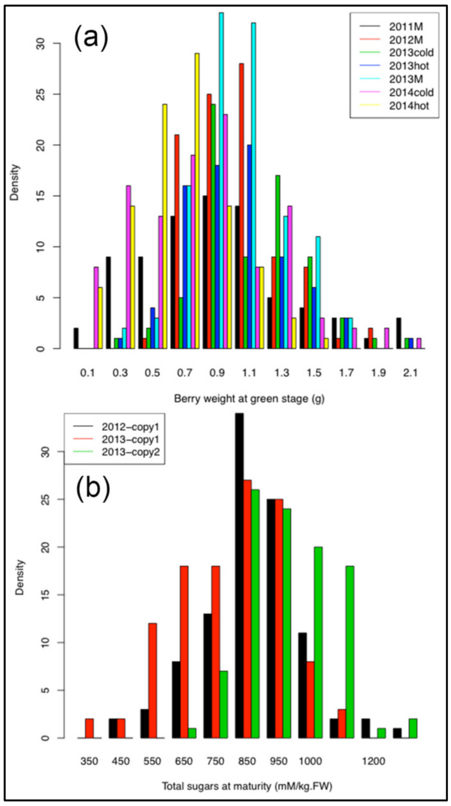

Figure 5 - (a) Berry weight and (b) sugar content individual distributions within the Picovigne x Ugni Blanc *flb* progeny.
M : mean value over two copies. T° in growth room : cool : day/night 20 °C/15 °C ; hot : day/night 30 °C/25 °C.

4. On the identification of genetic determinants of adaptation to T°

In this study, 14 QTLs showed a stable behavior with respect to environment fluctuations (Houel *et al.*, 2015). These regions include genetic traits controlling vegetative (e.g. leaf area) and reproductive (e.g. size and acidity of the berry) traits. These resources open new perspectives for future breeding programs. During our program, we have identified interesting phenotypes that could mitigate some negative effects of heat on berry development. Based on these resources, a new program has started to identify QTLs limiting sugar accumulation in the berry, as a major step to select cultivars more suitable for hot conditions (Figure 6).

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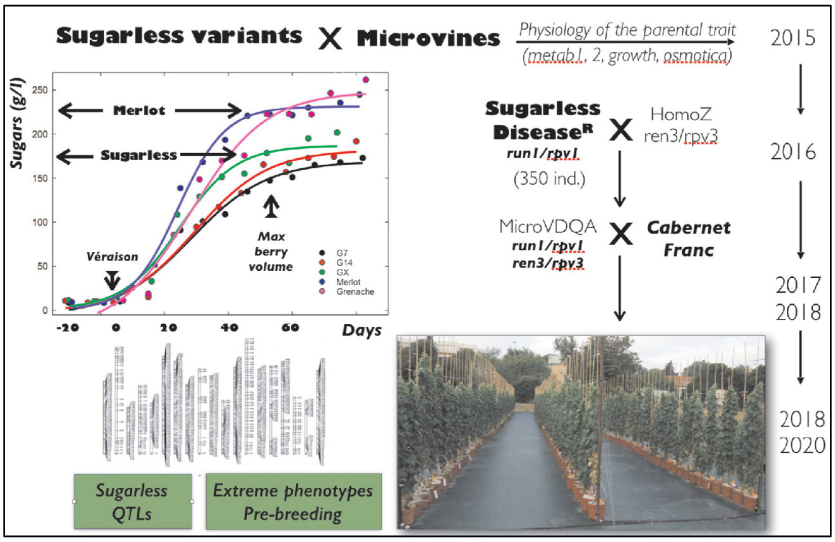

Figure 6 - Scheme of a genetic introgression to combine traits of berry adaptation to warming and plant tolerance to diseases using the microvine system.

Poupelain foundation, INRA, Montpellier SupAgro, CNIV (Comité National des Interprofessions des Vins à appellation d'origine) and CIVB (Comité Interprofessionnel des Vins de Bordeaux).

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Adapting plant material to face water stress in vineyards: which physiological targets for an optimal control of plant water status?

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Abstract

Aims: Water scarcity, associated with climate change, is a particular threat to the sustainability of viticulture in present areas of cultivation, usually prone to drought. Breeding grapevine for reduced water use, better water extraction and maintained production (i. e., high water use efficiency) is therefore of major interest.

Methods and results: This requires a comprehensive knowledge of the physiological impacts of drought on yield and quality. Attention should be paid to those mechanisms involved in the regulation of water status in plant tissues, as it is the primary parameter affected by drought. Transpiration rate, which has a major influence on plant water status, should therefore receive special attention in breeding programs. Beyond scions, the role of rootstocks, which have been largely introduced in vineyards, should be investigated further as it determines water extraction capacity and could modify water balance in grafted plants.

Conclusion: Here we review recent advances in the characterization of genetic variability in the control of water use and water status, whether induced by rootstock or scion.

Significance and impact of the study: This review should help scientists in choosing the relevant physiological targets in their research on grapevine tolerance to drought, whether for breeding prospects or new management practices.

Keywords: grapevine, drought, water use, rootstocks, genetics

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Introduction

Vineyards are predominantly located in drought prone areas. They commonly experience moderate soil water deficit, which is favorable to wine quality provided that it remains moderate (Becker and Zimmerman, 1984). Excess of water, by contrast, can reduce color intensity and sugar content of berries and produce unbalanced, flat wine (Matthews *et al.*, 1990 ; Medrano *et al.*, 2003). Thus, moderate soil water deficit is the best compromise to promote the expression of high enological potential without altering yield. This is usually achieved in most vineyards but global change seriously threatens this fragile equilibrium. Specifically, under the combined influence of high evaporative demand (dry, warm air) and soil water deficit, plant tissues start dehydrating with detrimental impacts on production and berry quality (Jones *et al.*, 2005 ; Deluc *et al.*, 2009).

To face transient drought or longer-lasting dry climates, irrigation is developing in production areas. However, pressure on agricultural use of water resources is rising. Irrigation of the vineyard often results as very competitive or impossible. To prepare for the future, viticulture should adapt by limiting water use while maintaining yield. Vineyard establishment and management practices, such as lower plantation density, control of water balance through soil surface management, and thinning, can be considered as valuable short-term solutions (Garcia de Cortazar Atauri, 2006 ; Duchêne *et al.*, 2010 ; Ripoche *et al.*, 2010). However, these techniques might not always be sufficient to cope with increasingly dryer conditions (Garcia de Cortazar Atauri, 2006). Additional strategies are needed, including the use of suitable plant material. This requires a comprehensive knowledge of the physiological impacts of drought on yield and quality.

In the following, we review the primary consequences of water deficit on grapevine. Specifically, genetic variability in the mechanisms involved in the control of plant water status is examined.

Physiological responses to water deficit

1. Drop in plant water potential as a primary consequence of water deficit

Water potential characterizes water availability from a thermodynamic point of view. Denoted Ψ, it is at the basis of water movements from the soil to the plant organs and ultimately to the atmosphere. Conventionally, free water at sea level has a potential of zero, corresponding to the maximal water availability in a saturated soil. Soil drying results in a

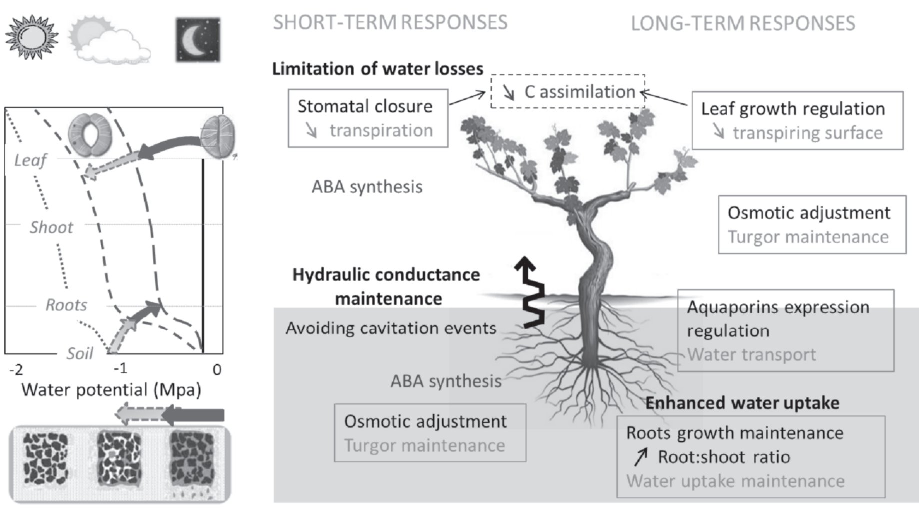

Figure 1. Physiological responses associated with a drop in plant water potential. Simplified representation adapted from Chaves *et al.* (2010) and Marguerit (2010).

The left diagram illustrates the drop of water potential occurring at different intensities depending on the soil water potential (dryer from right to left) and of the evaporative demand (higher from right to left). During the night, water potential equilibrates (vertical line). In the daytime, under high evaporative demand, plant water potentials become more negative (dashed lines) and further decline in dry soil (dotted line). Arrows indicate the influence of the physiological adaptations (limitation of water losses, maintenance of hydraulic conductance and enhanced water uptake) on water potentials, highlighting the favorable (filled, black arrows) and the unfavorable situations (dotted, grey arrows). The right diagram outlines the main physiological adaptations favoring the maintenance of plant water status. The negative consequences of a decrease in leaf water potential on carbon assimilation are also highlighted.

decrease of soil water potential (Ψ becomes more negative as water binds to soil particles and concentrating solutes). Under non transpiring conditions, water potentials in plants equilibrate with the most humid layer explored by the root system (Améglio *et al.*, 1999). As transpiration rate increases in the daytime, plant water potential decreases. This drop in water potential is more severe when hydraulic conductance is limiting water transport on the path from the soil through the plant to the leaves (Figure 1). Because excessive drops in water potential may be disastrous for plants, they have developed diverse adaptations to prevent them.

2. Cavitation threatens hydraulic integrity of xylem conduits

In a transpiring plant, sap water ascends towards the leaves using the non-living, heavily thickened and lignified xylem vessels and tracheids. Water flow follows a gradient of increasingly negative pressure within a continuous water column. Any break in this column would disrupt the whole water flow.

When soil drying combines with high evaporative demand, high tensile strength develops in the xylem, thereby favoring cavitation, which is the apparition of gaseous bubbles (caveats) in the xylem sap due to water evaporation, aggregation of dissolved gases or air entry through pit membranes. Once initiated the bubble then rapidly expands to overrun the vessel (Brodersen *et al.*, 2013). This gaseous embolism may result in the rupture of the water column in the xylem, being a major threat for the plant.

Vessel embolism decreases stem hydraulic conductance, which in turn decreases leaf water potential itself, favoring further embolism. In the absence of stomatal closure or reduction in leaf area, this cycle can result in functionality loss of all the conducting tissue. This results in dramatically amplified effects of water deficit on the drop in leaf water potential along the water path (Brodribb and Cochard, 2009 ; Zufferey *et al.*, 2011) with catastrophic consequences on plant dehydration and even death (McDowell *et al.*, 2008). Vessel size partly determines plant vulnerability to cavitation, small-diameter conduits being less vulnerable (Tyree, 2003) but less efficient to transport water. Thus, plant adaptation to dry environments depends on a trade-off between efficient conduits and low vulnerability to cavitation. In grapevine, which displays long vessels (a common feature among liana species), vessel sizes are dependent on the cultivar (Chouzouri and Schultz, 2005 ; Tramontini *et al.*, 2013a), leaving room for genetic variation in drought response.

Threshold water potential for cavitation also varies with species, cultivars and growth conditions. As compared to other species, grapevine has commonly been described as vulnerable to cavitation occurring at high (less negative) water potential threshold (Schultz and Matthews, 1988 ; McElrone *et al.*, 2012). Up to 70% loss of conductivity has been reported with moderate tensions in stems around -0.75 MPa (Tibbetts & Ewers, 2000). Nevertheless, an efficient control of water losses through stomata often protects grapevine from cavitation (Zufferey *et al.*, 2011).

Recent studies report that transport capacity could be largely restored by the end of the day or during the night, when transpiration rate decreases. This has been assigned to water refilling of embolized xylem vessels. Although mechanistically debated, restoration of water transport capacity has been observed in a number of species, whether in roots (Domec *et al.*, 2006 ; Lovisolo *et al.*, 2008a), shoots (Zwieniecki and Holbrook, 1998) or leaves (Johnson *et al.*, 2009). Plant capacity to restore hydraulic integrity over night under dry conditions would largely depend on soil exploration by roots (Zufferey *et al.*, 2011). Carbohydrates stored in cells neighboring the conducting vessels, together with aquaporins (e.g. membrane channel proteins facilitating water transport), also appear as possible, important actors of this restoration (Salleo *et al.*, 2009).

3. Limitation of transpiration releases hydraulic tension and saves water

One of the most obvious and immediate effects of water deficit is a reduction in shoot growth (Chaves, 1991), with cell expansion being particularly sensitive to water shortage (Hsiao, 1973). Branches are more sensitive than first order axes (Lebon *et al.*, 2006), and observation of growth cessation at the shoot apices is a powerful tool to early detect incipient water deficit (Pellegrino *et al.*, 2006). Limited vigor under drought results in a decrease of evaporative areas, thereby lowering transpiration and releasing water tension in the xylem. Leaf folding or wilting are other adaptations having similar, although reversible, effects on water saving by increasing boundary layer resistance and reducing intercepted light, hence lowering surface temperature and evaporative demand.

Additionally, plants dynamically modulate the aperture of stomata, those micropores located at the leaf surface that make possible water vapor and CO_2 exchanges. A rapid stomatal closure is generally observed under water deficit (Damour *et al*., 2010), which efficiently lowers water flow density. However, this way of saving water has a heavy cost for the plant because stomatal closure unavoidably lowers CO_2 uptake and decreases photosynthesis, although to variable extent depending on species and varieties (Tardieu and Simonneau, 1998). Plants thus face a dilemma, and adaptive strategies are necessary to reach a trade-off ensuring CO_2 uptake while limiting water losses.

Other adaptations may participate in minimizing transpiration rate, including changes in thickness and composition of the waxy cuticle that waterproofs the leaf surface and forces water to leave the plant through stomata. Relation between cuticle components and their efficacy to limit water losses remains to be understood (Riederer and Schreiber, 2001).

4. High root water extraction capacity postpones the negative impact of water deficit

Root development is highly plastic, with typical shifts in the allocation of plant's resources (carbohydrates) towards root growth at the expense of the shoots in dry conditions. This allows the plant to increase soil exploration for water uptake while reducing transpiration (Sharp and Davies, 1985 ; Cramer *et al*., 2013). The maintenance of root growth capacities during water deficit, together with some plasticity in root hydraulic architecture under fluctuating conditions, depend on the species and, in grapevine, is variable among rootstocks (Bauerle *et al*., 2008).

5. Osmotic adjustment helps maintaining water into the cells

Plants evolved in different ways to maintain physiological activity while water potential declines. A major response is osmotic adjustment, which allows the cells to maintain their water content and turgor even when water potential decreases in their vicinity. Osmotic adjustment in a cell consists of trapping or generating solutes to increase their concentration, leading to interactions of water with solutes inside the cell. This decreases the osmotic potential, a component of the total water potential, while turgor, the other component in cells, can be maintained even when a given drop in total water potential is transmitted to the cell from its environment.

This widespread response to water stress occurs in leaves, roots and reproductive organs of many species (Turner and Jones, 1980 ; Morgan, 1984) and is under genetic control (e.g. Teulat *et al*., 2001). In grapevine, osmotic adjustment has been evidenced under water deficit in leaves (Rodrigues *et al*., 1993) and roots (During and Dry, 1995). It might be a major strategy to avoid tissue dehydration and maintain grapevine production in dry conditions (Hare *et al*., 1998 ; Patakas and Noitsakis, 1999). The most interesting solutes are those that, besides their role in osmotic adjustment, play a role in nutrient or energy storage, membrane protection or detoxifying activities (Szabados *et al*., 2011).

6. Primary traits for a drought tolerant grapevine ideotype

Plant responses to drought are plural and involve a range of morphological and physiological adaptations of both aerial and underground organs. The primary features of interest for grapevine encompass a tight control of water losses through stomatal regulation, osmoregulation, together with photosynthesis maintenance to the benefit of berry development and root growth. The tight coupling between photosynthesis and transpiration, which are both controlled by stomata and leaf area, does not make trivial to decrease transpiration without altering photosynthesis. However, the ratio of photosynthesis to transpiration rates varies to some extent with environmental conditions and genotypes (Tomas *et al*., 2014 ; Medrano *et al*., 2015). An adequate control of stomatal aperture allows the plant to take advantage of the environmental conditions by lowering the water cost of gas exchange.

Physiological control of leaf water potential in a drying soil

1. The stomatal control of transpiration

Transpirational water losses, which, in combination with soil drying, are responsible for drawing down water potential in plants, mainly occur through the stomata. Stomata form microscopic pores mainly located on the abaxial (inferior) epidermis of the leaves in grapevine, a species therefore qualified as hypostomatous. A pair of adjacent guard cells controls the pore aperture through rapid modification in cell volume associated with turgor changes. Changes in turgor result either from variations in total water potential driven by soil or air drying (hydraulic response), or from active changes in osmotic potential caused by solute movements (into or out of the guard cells), themselves generated by chemical signals that modify ion transporter activity (biochemical response). Moreover, stomatal density displays a high inter-specific and intra-specific variability, as exemplified for grapevine (Boso *et al*., 2011). However, variability in stomatal density was not found to explain much of the differences in transpiration rate (Hopper *et al.*, 2014).

Stomatal closure in response to water deficit is controlled by abscisic acid (ABA), a plant hormone having long been recognized as a key player in plant abiotic stress responses (Loveys, 1984; Wilkinson and Davies, 2002; Yamaguchi-Shinozaki and Shinozaki, 2006). ABA biosynthesis, metabolism, and transfer towards guard cells modulate stomatal sensitivity to water deficit (Stoll *et al.*, 2000; Cramer *et al.*, 2007). ABA synthesis in roots was first proposed as the pivot of plant response to drought. Soil drying is sensed by the roots as their water potential decreases, resulting in an increased ABA biosynthesis by this compartment (Simonneau *et al.*, 1998). ABA is then conveyed to the leaves through the xylem vessels (Tardieu and Simonneau, 1998). ABA biosynthesis also occurs in the leaves (Holbrook *et al.*, 2002; Christmann *et al.*, 2005; Christmann *et al.*, 2007; Ikegami *et al.*, 2009) where hydraulic and chemical signals trigger foliar ABA synthesis in response to water deficit (Christmann *et al.*, 2013; Mittler & Blumwald, 2015), although the precise signal transduction still remains to be deciphered. Several key enzymes of the ABA biosynthetic pathway, namely ABA2, AAO3, and NCED3, are expressed in specific areas of vascular tissues in response to water deficit (Endo *et al.*, 2008). Importantly, *VvNCED1* coding for 9-cis-epoxycarotenoïd dioxygenase NCED, an enzyme catalyzing the first committed step in ABA biosynthesis, has been identified as decisive for ABA accumulation under water shortage in grapevine (Speirs *et al.*, 2013; Rossdeutsch *et al.*, 2016). Variations of pH between tissues, together with the action of glucosidases or glucosyl esterases, modify the concentration of free ABA reaching the stomata (Nambara and Marion-Poll, 2005). Depletion of ABA may also participate in the regulation of ABA balance. A specific group of enzymes, including the ABA 8'-hydroxylases, regulates ABA degradation to inactive compounds (Speirs *et al.*, 2013). A strong allelic diversity for genes involved in either ABA biosynthesis or degradation could explain genetic variations in ABA accumulation under water deficit (Nambara and Marion-Poll, 2005; Riahi *et al.*, 2013). In grapevine, variability in ABA accumulation has been observed among rootstocks (Peccoux, 2011) as well as scions (Soar *et al.*, 2004).

Additionally to ABA accumulation, stomatal sensitivity to the hormone is also highly variable (Tardieu and Simonneau, 1998; Rossdeutsch *et al.*, 2016). It depends on numerous molecular steps at the guard cell level. Perception of ABA corresponds to binding to the PYR/PYL/RCAR proteins (Brandt *et al.*, 2012). This leads to conformational change in the receptor enabling ABA interaction with PP2Cs phosphatase, which in turn releases SnRK2s kinases. SnRK2s activate transcription factors, ABA-responsive element Binding Factors (ABFs), which results in ABA-responsive gene expression (Klingler *et al.*, 2010; Boneh *et al.*, 2012). This cascade modulates the activity of ion channels in the guard cells, which translates in osmotic and turgor changes, and ultimately regulates stomatal closure (Joshi-Saha *et al.*, 2011). Many other actors involved in those responses have been identified, including variations in internal Ca^{2+} concentration and accumulation of nitrous oxide in guard cells.

How chemical control of stomatal aperture interacts with hydraulics is still a matter of debate. It has recently been proposed that ABA might affect leaf hydraulic conductance through a decrease in water permeability within leaf vascular tissues. ABA would thus promote stomatal closure in a dual way via effects on hydraulics upstream stomata and a direct biochemical effect on the guard cells (Pantin *et al.*, 2013). Variability in the role of ABA on hydraulic conductance remains to be explored as a possible cause of the large diversity of stomatal sensitivities to ABA observed among species and within grapevine cultivars.

2. Isohydric genotypes are able to maintain leaf water potential in drying soils

Soil drying inevitably results in a decrease of water potential in plants including leaves. However, contrasting controls of leaf water potential have been observed across species when submitted to similar soil water deficit conditions (Tardieu and Simonneau, 1998). So-called isohydric species, such as maize, efficiently maintain high leaf water potential in the daytime (Ψ_M) when the soil dries, whereas anisohydric species, such as sunflower, exhibit substantial decrease of Ψ_M (Tardieu *et al.*, 1996). In several species including the overall, roughly isohydric grapevine (Prieto *et al.*, 2010), a variable efficacy to maintain high Ψ_M has been observed across genotypes. Two widespread cultivars, namely Grenache and Syrah, have been consistently described with different responses to soil water deficit. Grenache was shown to be near-isohydric, compared with Syrah, which exhibited more anisohydric behavior (Schultz, 2003; Soar *et al.*, 2006b).

The classical view relates the contrasted (an)isohydric behaviors to the more or less efficient control of transpiration rate by stomatal closure (Buckley, 2005). Stomatal conductance was shown to decrease earlier during the course of a soil drying episode in isohydric species, thus reducing the drop of leaf water potential in the daytime as compared to anisohydric species (Tardieu and Simonneau, 1998). The anisohydric behavior would thus favor photosynthesis maintenance under water deficit. This has been confirmed in grapevine (Lovisolo *et al.*, 2010) where anisohydric cultivars also exhibit higher vigor in conditions of water deficit (Pou *et al.*, 2012), as long as soil drying does not induce any serious decrease of plant water potential. Anisohydric plants might also be more resistant to cavitation than isohydric ones (Schultz, 2003 ; Alsina *et al.*, 2007) and might easily recover from partial cavitation events, thus exhibiting a higher tolerance to moderate water deficit events. However, beyond a certain threshold in soil drying, the anisohydric behavior might not remain favorable because high levels of dehydration lead to serious damages. This has been exemplified for grapevine cultivars such as Syrah and Chardonnay (Alsina *et al.*, 2007). By contrast, the isohydric cultivar Cabernet-Sauvignon displays a reduced photosynthesis but is preserved against damages such as photoinhibition, which is the alteration of photosynthesis due to high light intensity (Hochberg *et al.*, 2013). Hence, one of these behaviors can be more interesting depending on the water deficit scenario (duration, intensity, combination with evaporative demand). While anisohydric cultivars may be recommended in the case of short periods of moderate water deficit because they sustain production, the isohydric ones appear as more suitable to face long lasting periods of severe drought. Specificities of the climatic scenarios should be considered to define the more advantageous type of cultivar from an agronomic point of view.

3. Reconsidering the origin of the variation in (an)isohydric behaviors

The classical view of (an)isohydry was recently questioned in several studies. It was proposed that changes in hydraulic conductance may contribute, concurrently with stomatal regulation, to the control of Ψ_M under adverse conditions (Franks *et al.*, 2007 ; Pantin *et al.*, 2013). Additionally, (an)isohydry would not be a genotype-constitutive feature (Lovisolo *et al.*, 2010) but could vary in a same plant following season and development (Poni *et al.*, 1993 ; Chaves *et al.*, 2010). Some studies concluded to variable ranking of (an)isohydric behaviors between grapevine cultivars, notably Grenache and Syrah (Pou *et al.*, 2012). The genetic origin of (an)isohydry was thus challenged.

Genetic variation in (an)isohydry was extensively studied in grapevine using a mapping population obtained from a cross between Syrah and Grenache (Coupel-Ledru *et al.*, 2014). Significant genetic control of Ψ_M under moderate drought was observed under controlled conditions using potted plants in a phenotyping platform. Several genomic regions (QTLs) were identified as underlying the genetic variation of Ψ_M. Further, the maintenance of Ψ_M under water deficit conditions was not simply controlled by transpiration response to soil drought. Some of the QTLs detected for genetic variation in Ψ_M response to moderate water deficit collocated with QTLs for transpiration response, but others collocated with QTLs detected for plant hydraulic conductance (Coupel-Ledru *et al.*, 2014). Overall, genetic variation of Ψ_M under water deficit conditions correlated with variation in plant hydraulic conductance (Coupel-Ledru, 2015). It was thus proposed that whole plant hydraulic conductance under water deficit might combine with stomatal control of transpiration to determine (an)isohydry. Specifically, variation in (an)isohydry may result from slight deviation in the balance between transpiration rate and hydraulic conductance.

The genetic analysis of the Syrah × Grenache offspring (Coupel-Ledru *et al.*, 2014) also evidenced that transpiration rate and soil-to-leaf hydraulic conductance mostly correlated. This may explain why grapevine can be considered as roughly isohydric by contrast with other species like sunflower where more severe drops in Ψ_M rapidly occur as the soil dries (Tardieu *et al.*, 1996). In grapevine, this balance may be the result of multiple coordination between stomatal response and variation in specific hydraulic conductance in leaves (Pou *et al.*, 2012), petioles (Schultz, 2003) and roots where correlation with expressions of water channel proteins in roots has been evidenced (Vandeleur *et al.*, 2009). Identification of genes specifically associated with QTLs detected for hydraulic conductance and control of Ψ_M but not for transpiration response (and vice versa) would be of particular interest to look for origins of possible imbalance between transpiration and water transport capacity and to progress on the determinism of (an)isohydry.

Rootstocks : the hidden half

While the choice of scion varieties is often regulated by their performance in specific climatic conditions or marketing purposes (van Leeuwen and Seguin, 2006), rootstocks offer more flexible solutions for adapting the grafted plant to drought. A large variability in rootstock response to water deficit has been reported by several authors (Carbonneau, 1985 ; Ollat *et al.*, 2016 ; Zhang *et al.*, 2016), although underlying mechanisms still need to be enlightened. Rootstocks participate in the regulation of plant water balance through their own uptake capacities associated with root growth and water transport (Carbonneau, 1985 ; Bauerle *et al.*, 2008 ; Alsina *et al.*, 2011 ; Peccoux, 2011 ; Zhang *et al.*, 2016) or via their effects on stomatal regulation (Lovisolo *et al.*, 2010 ; Marguerit *et al.*, 2012) and above ground development (Jones, 2012). Water extraction capacities by roots are reported to be variable between rootstocks and genetically controlled (Carbonneau, 1985 ; Soar *et al.*, 2006a ; Marguerit *et al.*, 2012), even though the physiological mechanisms underlying this trait are still unknown. In addition, rootstocks are known to affect scion phenology, vegetative growth, yield and fruit quality (Tandonnet *et al.*, 2010).

1. Root development to better explore soil water resources

A deep and dense root system favors water uptake to compensate for water losses by transpiration. Grapevine is known for its ability to grow deep roots. Root distribution and root system architecture are more affected by soil type and training system than by rootstock genotype (Smart *et al.*, 2006). In addition, interactions with scion genotypes have a strong effect on root system development (Tandonnet *et al.*, 2010). By contrast, rootstock genotype has more impact on root density expressed as biomass - or root number by volume of soil - (Southey and Archer, 1988 ; Peccoux, 2011), or on the ratio of fine roots to total roots (Van Zyl, 1988). In the vineyard, some highly drought tolerant rootstocks such as 140Ru are more able to grow roots in deep soil layers (Southey and Archer, 1988). Furthermore, the maintenance of root growth under dry conditions as well as the root system plasticity with soil water status may differentiate rootstock genotypes (Bauerle *et al.*, 2008) according to their strategy to cope with drought (Comas *et al.*, 2010). Further investigations of root growth properties for different rootstocks would be profitable for the future.

2. The control of water transport to shoot

The root system contributes in a non-negligible way to the whole plant resistance to water flow (Steudle, 2000). There is a large variability among rootstocks in root vascular anatomy (vessel diameter and length, percentage of conducting tissues ; Pongracz & Beukman, 1970 ; Alsina *et al.*, 2011 ; Peccoux, 2011). These differences can affect root ability to convey water to the canopy (i. e. hydraulic conductance), and root vulnerability to cavitation. Differences between rootstocks for root hydraulic conductance have been reported (de Herralde *et al.*, 2006 ; Peccoux, 2011 ; Tramontini *et al.*, 2013b), but may be more related to whole root system size than individual root properties (Alsina *et al.*, 2011). In addition, drought effect on root hydraulic conductivity may differ between rootstocks. Barrios-Masias *et al.* (2015) observed a lower decrease of root conductivity for the drought tolerant rootstock 110R, in comparison to the drought sensitive 101-14MGt. Differences are related to the development of suberized apoplastic barriers in the root tips at the beginning of the maturation zone. In grapevine, roots together with leaves are more sensitive to embolism than the other plant compartments (Tramontini & Lovisolo, 2016). Besides, it was recently shown that wild *Vitis* species stems differ for their sensitivity to cavitation under water stress and their ability to repair after rehydration, paralleling contrasting responses of root pressure to re-watering associated to osmotic regulation (Knipfer *et al.*, 2015).

Without any doubt, these facts have specific, molecular origins in the context of grafted plants. Transcriptomic analyses in the root tissues of various rootstock-scion combinations submitted to long term water deficit support the involvement of cell wall and osmotic metabolisms in the variability of responses among rootstocks (Peccoux, 2011).

3. Aquaporins as key actors in transmembrane water transport

The ability to drive water from root tips to stomata does not only depend on vascular pathways. Water also follows inter- and intracellular pathways that are under the control of water channel proteins embedded in cell membranes, named aquaporins (Maurel *et al.*, 2015). The genes encoding for such proteins have been identified for grapevine (Fouquet *et al.*, 2008 ; Shelden *et al.*, 2009). Their expression has been reported in different plant compartments, various genotypes and under drought conditions (Galmes *et al.*, 2007 ; Gambetta *et al.*, 2012 ; Rossdeutsch, 2015). Some of these genes are more expressed in root tips than in more mature suberized zones of the roots where the radial hydraulic conductivity is lower (Gambetta *et al.*, 2013). Differences have been reported among rootstock genotypes for the expression of these genes under well-watered and drought conditions, or for the proportion of conductance under the control of aquaporins (Lovisolo *et al.*, 2008b; Gambetta *et al.*, 2012; Rossdeutsch, 2015). Although the expression of some aquaporin genes like *VvPIP1;1* in roots appears to correlate with hydraulic conductance and plant transpiration (Vandeleur *et al.*, 2009), the situation in a grafted plant is much more complex and scion effects have to be considered as well (Tramontini *et al.*, 2013b; Rossdeutsch, 2015). Rootstocks also present contrasting abilities to produce ABA under drought conditions (Rossdeutsch *et al.*, 2016) and the interactions of chemical and hydraulic signals of soil water status from rootstock to scion should be taken into account. The role of ABA in the control of the expression and activity of aquaporins is now clearly established (Finkelstein, 2013; Grondin *et al.*, 2015).

4. Genetic architecture for transpiration and growth as controlled by rootstock

The genetic architecture for water deficit responses induced by rootstock remains poorly studied (Marguerit, 2010; Marguerit *et al.*, 2012). Specifically, it can be questioned to what extent transpiration, growth and water use efficiency are genetically controlled by the rootstock. This question has been addressed in a 3-year experiment using a pedigree population issued from the cross between *V. vinifera* Cabernet Sauvignon × *V. riparia* Gloire de Montpellier made up of 138 individuals. Transpiration rate, $\delta^{13}C$ (a proxy for water use efficiency), transpiration efficiency (ratio of biomass produced to water transpired), water extraction capacity and the response of transpiration to water deficit were characterized. Broad sense heritability was above 0.3 for most traits, although with significant year effects highlighting the strong impact of the environment. Few significant correlations were found between traits. As mentioned above for scions, traits related to genetic variability in rootstock exhibited a polygenic control as revealed by the detection of multiple QTLs. One QTL for water extraction capacity was identified in the three years on linkage group 3, confirming the hypothesis proposed by Carbonneau (1985) and Soar *et al.* (2006a) that this trait was genetically controlled at the rootstock level. A genetic architecture of transpiration plasticity to water deficit was evidenced which was partially independent from the genetic architecture of transpiration rate, suggesting an independent selection process for these two traits. Riparia Gloire de Montpellier, reputed as sensitive to water deficit, early reduced its scion transpiration as the soil was drying. The genetic architectures of $\delta^{13}C$ and transpiration efficiency were partially independent, underlining the complexity of selecting plant material for water use efficiency (Condon *et al.*, 2004). Transpiration efficiency appeared to be less influenced by climatic (year) effect and soil water conditions, and could therefore be more easily used for breeding. The QTLs detected in the offspring included genes that have been characterized as potentially involved in water deficit responses (Marguerit *et al.*, 2012). Candidate genes related to hormone (notably ABA) and hydraulic (aquaporins) signaling between the rootstock and the scion are particularly interesting as they play a major role in water deficit responses (Soar *et al.*, 2006a; Vandeleur *et al.*, 2009).

This review and other data collected on rootstocks show that drought tolerance may probably be acquired through different mechanisms (Serra *et al.*, 2014; Rossdeutsch *et al.*, 2016). This diversity should be taken into account to adapt plant material to different situations and levels of water deficit.

Conclusions

Grapevine response to water limitation is complex and involves many physiological mechanisms. Genetic variability has been described for several traits related to these mechanisms and many associated genomic regions have already been identified at the scion and rootstock levels. Better knowledge on the role of favorable alleles in these regions will help designing adequate plant material to deal with the increased risk of drought events in the context of climate change.

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The VitAdapt project: extensive phenotyping of a wide range of varieties in order to optimize the use of genetic diversity within the *Vitis vinifera* species as a tool for adaptation to a changing environment

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Abstract

Aim: Variability among cultivars is a precious resource to adapt viticulture to a changing environment. The aim of the VitAdapt project is to provide data from extensive phenotyping of a wide range of *Vitis vinifera* cultivars in order to optimize the use of this resource.

Methods and results: The VitAdapt experimental block was planted in 2009 with 52 cultivars (31 reds and 21 whites). Each variety was planted with 5 replicates to rule out a possible soil effect. Since 2012, all varieties have been phenotyped for phenology, grape ripening dynamics, yield components, pruning weight and water use efficiency. Since 2015, leaf blade and petiole mineral analyses and micro vinifications have been implemented.

Conclusions: The extreme phenotypic diversity among *Vitis vinifera* cultivars was confirmed. In 2015, bud break, flowering and veraison took place over a time span of 24, 16 and 40 days, respectively. Maximum sugar content ranged from 209 g/L (Chasselas) to 266 g/L (Carignan). These results can be used to maintain the best possible fit between the grapevine variety and the climate in a changing environment.

Significance and impact of the study: Although the great variability within the *Vitis vinifera* species is a valuable resource for adaptation, precise phenotypical data for cultivars is limited. Most existing data is acquired in cultivar repositories which are not planted with replicates, which makes it impossible to separate variability induced by variations in soil type or depth from genotypic variability. The VitAdapt project provides high quality phenotypical data for 52 cultivars for major characteristics of grapevine cultivars.

Key words: *Vitis vinifera*, phenotyping, adaptation, *genotype x environment* interactions, climate change

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Introduction

Like any agricultural crop, vines interact with their environment, in particular soil and climate. These interactions are driving yield and grape composition responses (van Leeuwen and Seguin, 2006). Among environmental factors, climate is changing from year to year (the so-called "vintage effect", Jones and Davis, 2000). Moreover, due to excessive emissions of greenhouse gases, a clear trend to a warmer, and in some locations dryer, climate is observed worldwide (IPCC, 2014). In order to optimize yield and quality potential, growers can adapt to a changing environment through management practices and plant material (van Leeuwen and Destrac, 2017). A grapevine generally consists of a scion grafted onto a rootstock (Keller, 2010). Both genotypes provide phenotypic variability. Variability induced by the cultivar is huge and provides a highly interesting tool for adaptation. Many cultivar comparisons are available in the scientific literature (among others, see Huglin and Schneider, 1998). However, the conditions in which the data were collected are rarely accurately described. Most of the time, phenotyping was performed in cultivar repositories where vines are not planted with replicates. Because soil is never fully homogeneous, it is impossible to separate a possible soil effect from a cultivar effect. The VitAdapt (for *Vitis* Adaptation) project was set up in the Bordeaux area (France) to phenotype a wide range of *Vitis vinifera* cultivars with an experimental design allowing to take into consideration *genotype x environment* interactions. Data are collected over a long period of time, allowing the assessment of *genotype x climate* interactions by taking into account the effect of inter annual climatic variability. Major phenotypical traits measured are phenology, yield, grape ripening dynamics, grape composition at ripeness, water use efficiency, pruning weight and leaf blade and petiole mineral composition.

Materials and methods

1. Selection of the parcel, plantation and training system

The VitAdapt parcel has been planted on the Institut National de Recherche Agronomique (INRA) research station in 33140 Villenave d'Ornon, next to the Institut des Sciences de la Vigne et du Vin (ISVV) at 44°47'23.83 N", 0°34'39.3" W. Villenave d'Ornon is located close to the town of Bordeaux (France). Prior to plantation, an area close to 10 ha was investigated by electric tomography (Tabbagh *et al.*, 2000). A parcel of 0.72 ha was selected for the VitAdapt experiment in the most homogeneous part of the investigated area (figure 1).

During soil preparation, the North-Western part of the parcel was identified as being prone to water logging and was subsequently excluded (figure 2). Guard vines were planted at the four borders of the parcel. The final design, including guard vines, accounts for 46 rows of 75 vines (row spacing 1.8 m; inter vine spacing 1.0 m; density 5,555 vines/ha). Trunks are

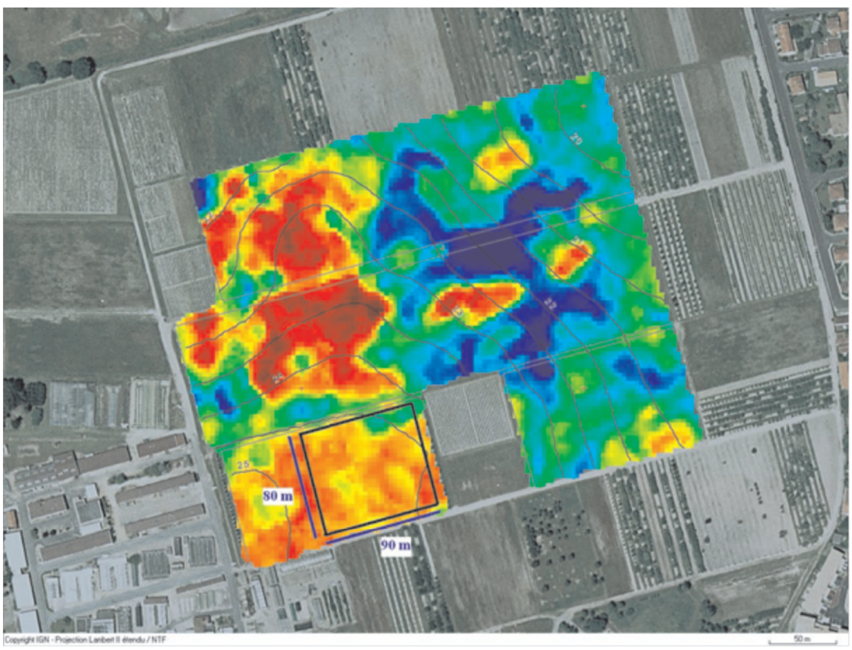

Figure 1. Soil resistivity map of the area for potential planting of the VitAdapt parcel. The most homogeneous area was selected (black box).

established at 0.5 m above the soil surface, grapevines are pruned as double guyot (leaving 4 to 6 buds on each cane, depending on vine vigor) and hedged at 1.6 m. Cover crop is maintained every second row (alternating every year) and weeds are controlled underneath the row by mechanical tillage. Diseases are controlled by integrated pest management practices.

2. Plant material

The list of grapevine varieties to be studied in VitAdapt was established according to several objectives. Major grapevine varieties planted worldwide should be present in the VitAdapt project (Anderson and Aryal, 2013). Although its planting acreage is very high, the white variety Airen was excluded, because it is only present in the Spanish La Mancha area. Since the experimental block is located in the production area of Bordeaux wines, all major varieties of this region were introduced. A major objective of the project was to study the adaptation of cultivars to a changing climate. For this reason, some late ripening varieties were selected, being potential candidates for mid- to long-term introduction in the Bordeaux winegrowing area as an adaptative response to climate change. Five non-*vinifera* hybrids were also introduced. The combination of these criteria led to a total of 52 varieties, 31 reds and 21 whites (table 1). Plant material was sourced from various origins (table 1). All material was tested for the absence of major virus diseases (Grapevine Fan Leaf Virus or GFLV, Arabis Mosaic Virus or ArMV and Grapevine Leaf Roll Virus or GLRaV-1, GLRaV-2 and GLRaV-3). As no virus-free material was found for Agiorgitiko, this variety was cleaned by *in vitro* shoot apex micrografting. For varieties for which clones were available, major clones, and if possible clones known for producing high quality wines, were selected. All varieties were grafted onto SO4 clone 761 rootstock. Plantation took place in 2009, except for some varieties which were planted in 2010 due to the availability of plant material. Agiorgitiko was introduced in 2015 when clean material was obtained.

Five blocks were designed and sub-plots of 10 vines for each variety were randomly distributed over each block (figure 3). In each block, the sub-plots of 10 vines were planted in two consecutive rows (5 vines on each row, surrounded by vineyard posts).

3. Data acquisition

To optimize data acquisition, a bar coding system was set up to identify each replicate for each variety (figure 4). The code refers to row number, inter-post number, grape variety number, block number, grape variety color (0 = white ; 1 = red) and location number. After scanning the bar code, data acquisition, like bud counts or any other quantified observation, is carried out with a portable data logger (CIPHERLAB 8300 mobile computer, 10669, Taipei, Taiwan). Data can be automatically downloaded from the data logger to the computer. The VitAdapt project generates large amounts of data. In order to store data and make it accessible as a useful resource for the scientific community working on plant phenotyping and *genotype x environment* interactions in grapevine, a database named VitPhe for *Vitis* Phenotyping was developed. Part of the acquired data is publicly accessible at http://bioweb.supagro.inra.fr/vitphe/public/.

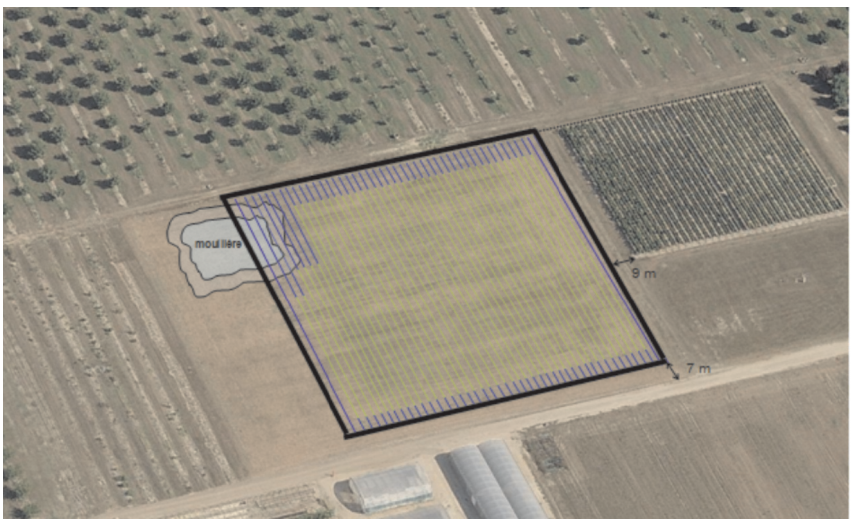

Figure 2. Delineation of the planted area in the VitAdapt block. Guard vines are in violet.

Table 1. The grapevine cultivars included in the VitAdapt project, 31 red grape cultivars and 21 white grape cultivars. NC : non-commercial clone or unknown clone ; CC : clone from collection ; white cultivars ; red cultivars ; hybrid cultivars ; Montp = Montpellier ; Bx = Bordeaux ; ENTAV = Etablissement National Technique Amélioration Viticulture, 30240 Le Grau-du-Roi ; VASSAL = Domaine de Vassal INRA, 34340 Marseillan ; CA = Chambre d'Agriculture

Nr	Cultivars	Origin	Source	Clone	Plantation
1	Alvarinho	Spain	-	-	2010
2	Agiorgitiko	Greece	-	-	2015
3	Arinarnoa	France	INRA Bx	723	2009
4	Assyrtiko	Greece	VASSAL	NC	2009
5	BX 648 Red	France	INRA Bx	NC	2009
6	BX 9216 White	France	INRA Bx	NC	2009
7	Cabernet franc	France	CA 33	327	2009
8	Cabernet-Sauvignon	France	CA 33	412	2009
9	Carignan	France	ENTAV	65	2009
10	Carmenère	France	CA 33	1059	2009
11	Castets	France	INRA Bx	CC	2009
12	Chardonnay	France	INRA Bx	95	2009
13	Chasselas (réf précoce')	France	INRA Bx	887	2009
14	Chenin blanc	France	ENTAV	1018	2009
15	Colombard	France	CA 33	605	2010
16	Cornalin	Switzerland	INRA Bx	NC	2009
17	Cot	France	CA 33	1061	2009
18	Gamay (réf précoce')	France	ENTAV	358	2009
19	Grenache	France	ENTAV	513	2009
20	Hibernal	Germany	Geisenheim	NC	2009
21	Liliorila (Baroque * Chardonnay)	France	INRA Bx	734	2009
22	Marselan	France	ENTAV	980	2009
23	Mavrud	Bulgaria	-	-	2010
24	Merlot	France	CA 33	347	2009
25	Morrastel (Graciano)	France	ENTAV	949	2009
26	Mourvèdre	France	ENTAV	369	2009
27	MPT 3156-26-1 White	France	INRA Montp	NC	2009
28	MPT 3160-12-3 Red	France	INRA Montp	NC	2009
29	Muscadelle	France	CA 33	610	2009
30	Verdejo	Spain	-	-	2015
31	Petit Manseng	France	CA 64	573	2010
32	Petit Verdot	France	CA 33	1058	2009
33	Petite Arvine	Switzerland	INRA Bx	NC	2009
34	Pinot noir	France	ENTAV	667	2009
35	Prunelard	France	Gaillac	CC	2009
36	Riesling	France	INRA Bx	49	2009
37	Rkatsiteli	Georgia	INRA Bx	NC	2009
38	Roussanne	France	ENTAV	468	2009
39	Sangiovese (Niellucio)	Italy	ENTAV	903	2009
40	Saperavi	Georgia	INRA Bx	NC	2009
41	Sauvignon blanc	France	CA 33	108	2009
42	Sémillon	France	CA 33	908	2009
43	Syrah	France	CA 11	470	2010
44	Tannat	France	CA 64	474	2010
45	Tempranillo	Spain	ENTAV	771 ou 770	2009
46	Tinto Cao	Portugal	VASSAL	CC	2009
47	Touriga Franca	Portugal	VASSAL	NC	2009
48	Touriga Nacional	Portugal	INRA Bx	NC	2009
49	Ugni blanc	France	CA 33	384	2009
50	Vinhao (Souzao)	Portugal	-	-	2010
51	Viognier	France	ENTAV	1051	2009
52	Xinomavro	Greece	-	-	2010

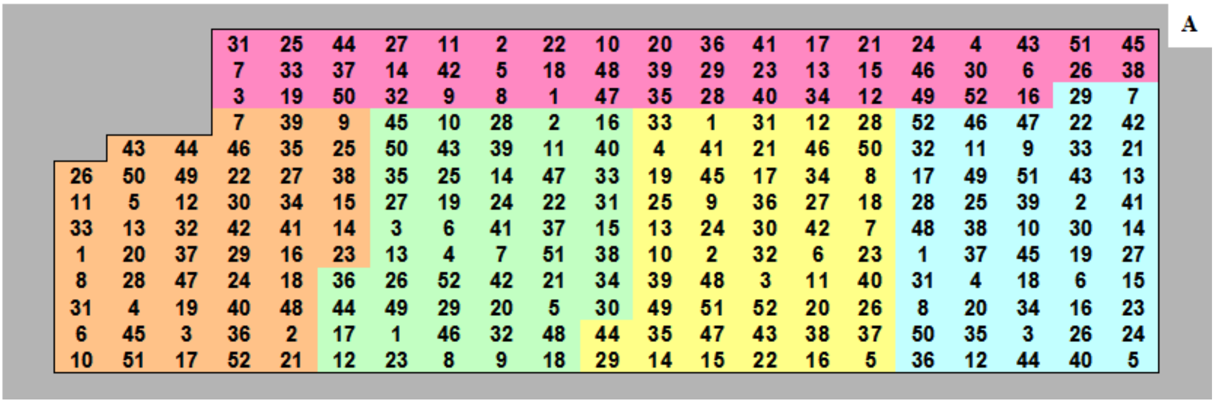

Figure 3. Distribution of the 52 varieties of the VitAdapt parcel over the 5 blocks. Numbers refer to varieties presented in Table 1. Block 1 in pink, block 2 in orange, block 3 in green, block 4 in yellow and block 5 in blue.

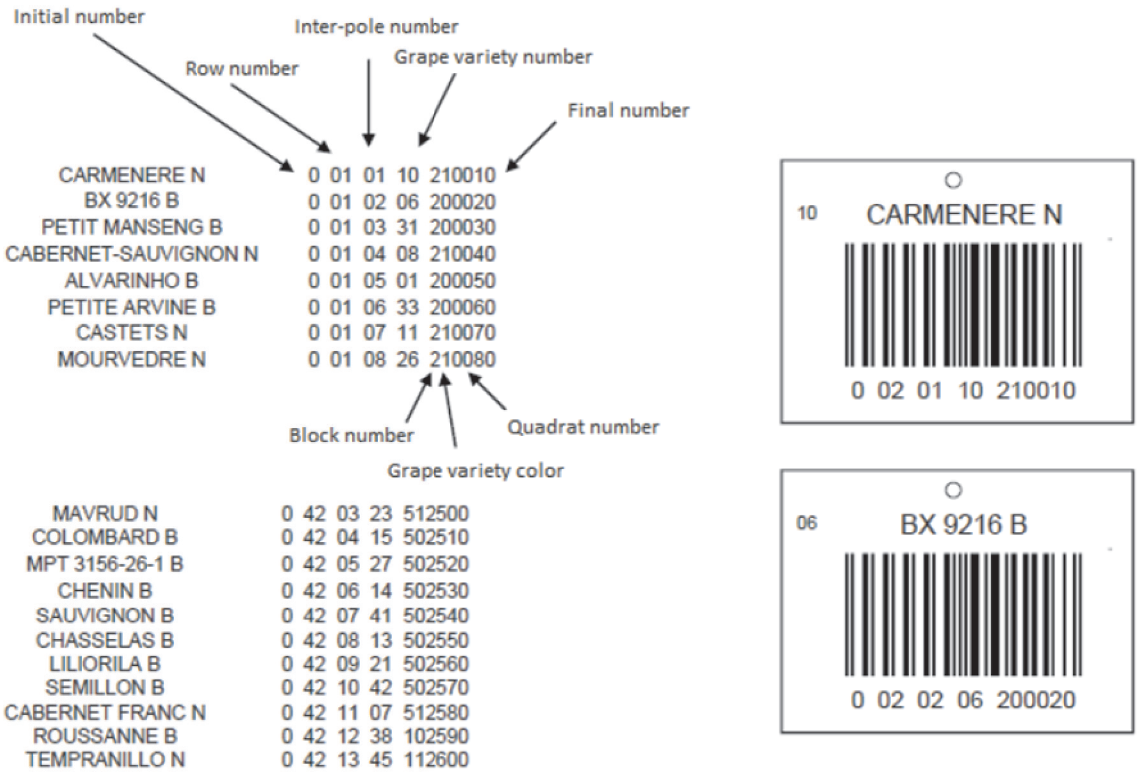

Figure 4. Bar code system for variety and replicate identification.

4. Data collected

- Phenology

Bud break, flowering and veraison dates are assessed for each replicate of each variety since 2012 using the BBCH scale (Lorenz *et al.*, 1995). For bud break, total number of buds left after pruning is counted. Crown buds are not counted. A bud is counted as burst when a green or red tip is visible and only primary buds are observed. Progression in the % of bud burst is assessed by three observations each week. The BBCH07 stage corresponds to the date when 50 % of buds are burst when compared to the total number of buds left after pruning. Flowering is assessed by estimating the percentage of open flowers three times a week. The date when 50 % of flowers are open is recorded, which corresponds to BBCH stage 65. Veraison is assessed by touching 50 berries of each replicate and each variety three times a week and the percentage of soft berries is recorded. The date when 50 % of the berries are soft corresponds to BBCH stage 85.

- Grape ripening dynamics

A major challenge is the implementation of weekly grape juice analyses for each replicate of each variety from veraison to harvest (260 analyses each week). At each sampling date, 60 berries are manually sampled from each replicate and each variety. In the laboratory the berry samples are counted and weighed to determine berry weight. The juice is then extracted by pressing the berries between two metal blades (Bagmixer 400W - Interscience, France) and then filtered (Lateral BagFilter - Interscience, France) before being centrifuged at 20 °C for 10 minutes at 10,000 rpm. The recovered supernatant (minimum 12 mL) is then analyzed. Brix is manually determined with an electronic refractometer (Digital Refractometer, Ningbo Gamry Optical Instrument Co., Ltd.). Then juice samples (12 mL) are analyzed by Fourier Transform InfraRed Spectroscopy (FTIR), using a WineScan™ analyzer according to the method "Must" provided and calibrated by the manufacturer (FOSS, 92000 Nanterre, France). Each sample is analyzed twice. The WineScan™ was previously calibrated for total acidity, malic acid and Yeast Available Nitrogen (Destrac *et al.*, 2015). For titratable acidity, samples are diluted 1/4 or 1/8 depending on the stage of maturity and analyzed by titration with sodium hydroxide using an automatic titrator (Cogétude, 41100 Vendôme, France). For malate and tartrate, samples are analyzed on a continuous flow analyzer (800 trAAcs BRAN-LUEBBE). Malate is determined by enzymatic assay (adaptation of the method OIV-MA-AS313-12A) and tartrate by colorimetric assay (OIV-OENO 391-2 010 F). The Yeast Assimilable Nitrogen is evaluated by formol titration (Sørensen formol titration, Aerny, 1996). Sugar and NH_4^+ are analyzed by enzymatic assay (Biosentec, 31120 Auzeville, France and Boehringer Mannheim, Germany, respectively). Potassium is measured by Flame Spectrometry (Thermo AA, Fischer Scientific, USA).

Berry weight is assessed once a week from mid-veraison to harvest on the same sample collected for berry composition. Each lot of 60 berries is weighted to determine average berry weight. Number of bunches per vine is counted once on each replicate of each variety prior to harvest and average bunch weight is determined at harvest. However, bunch weight is impacted by grape sampling and occasionally by Botrytis, which limits the reliability of bunch weight data.

- Pruning weight

Pruning is carried out during the first three weeks of January. Pruning wood weight is assessed on three plants per block (woods from the three vines are pooled), using a manual balance.

- Water Use Efficiency

Water Use Efficiency is estimated by determining $^{13}C/^{12}C$ isotope ratio on sugars produced by photosynthesis (Farquhar *et al.*, 1989). When measured on grape sugars, this ratio, also called $\delta^{13}C$ when expressed against a standard, is a precise indicator of vine water status during sugar loading in grape berries, which takes place in the 3 to 4 weeks after veraison (Gaudillère *et al.*, 2002). $\delta^{13}C$ is determined on grape berries at ripeness since 2012. A second measurement of $\delta^{13}C$ on grape sugars was introduced in 2015 and 2016 on a fixed date for all varieties.

- Petiole and leaf blade analyses

N, P, K, Mg and Ca content in leaf blades and petioles were measured since 2015 on a subset of 37 varieties. The analyses are carried out at mid-veraison on primary leaves sampled in the cluster zone. Ten leaves and petioles are sampled for each variety and block. Analyses are performed by Aurea Agrosciences, 17074 La Rochelle, France.

- Climatic parameters

Climate data was collected in a weather station near the VitAdapt parcel. Hourly temperatures, rainfall, wind speed and reference evapotranspiration were recorded and stored in Climatik, a database managed by INRA, US 1116 Agroclim research station, 84914 Avignon, France: https://intranet.inra.fr/climatik_v2 (limited access).

- Drought symptoms

In 2016 and 2017, which were exceptionally dry years from the end of June until harvest, the varieties present in the VitAdapt parcel showed various levels of drought symptoms. Intensity of leaf necrosis and berry shrivel were recorded for each replicate of each variety.

- Micro vinifications

A subset of 22 varieties was annually vinified since 2015. Ten kilograms of grapes were processed in standardized conditions and wines were analyzed (chemical and sensory analyses). Micro vinifications were not replicated.

5. Other services provided

The VitAdapt parcel is located close to the ISVV where several curriculums at Bachelor, Master and PhD level are being offered. The VitAdapt parcel provides an exceptional set-up to train students to ampelography. Although VitAdapt was not primarily intended to test resistance to diseases, plant health scientists occasionally carry out observations comparing levels of diseases among the VitAdapt varieties. VitAdapt also provides cuttings for researchers requiring plant material for some specific varieties.

Discussion and conclusions

Although the great variability within the *Vitis vinifera* species is a valuable resource for adaptation, accurate phenotypical data for cultivars are limited. Most existing data have been collected in cultivar repositories which have not been planted with replicates, making it impossible to separate environmental from genotypic variability. The VitAdapt project provides high quality phenotypical data for 52 cultivars for major characteristics of grapevine cultivars. Because data are acquired over a long time span, the effect of climatic variations (both vintage climatic variability and long-term climate trends) on vine physiology and grape composition is assessed, making it possible to study *genotype x environment* interactions. The accurate phenological data and the presence of a weather station on site can be used to develop, improve or validate phenological models. Grape composition and berry weight data can be used to develop models for grape ripening dynamics. $\delta^{13}C$ data can be used to assess differences in water use efficiency among varieties, in relation to their drought resistance. Leaf blade and petiole mineral composition will help to develop varietal-specific thresholds for data interpretation. On a more global scale, VitAdapt will help to assess which varieties are better adapted to a warmer and dryer climate in order to optimize the use of the genetic diversity within the *Vitis vinifera* species as a potential tool for adaptation to climate change.

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Combining ecophysiological models and genetic analysis: a promising way to dissect complex adaptive traits in grapevine

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Abstract

Designing genotypes with acceptable performance under warmer or drier environments is essential for sustainable crop production in view of climate change. However, this objective is not trivial for grapevine since traits targeted for genetic improvement are complex and result from many interactions and trade-off between various physiological and molecular processes that are controlled by many environmental conditions. Integrative tools can help to understand and unravel these Genotype × Environment interactions. Indeed, models integrating physiological processes and their genetic control have been shown to provide a relevant framework for analyzing genetic diversity of complex traits and enhancing progress in plant breeding for various environments. Here we provide an overview of the work conducted by the French LACCAVE research consortium on this topic. Modeling abiotic stress tolerance and fruit quality in grapevine is a challenging issue, but it will provide the first step to design and test *in silico* plants better adapted to future issues of viticulture.

Mots clés: Process-based models, climate change, adaptation, G×E interaction, grapevine

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Introduction

Exploiting genetic diversity or designing new scion varieties and rootstocks with better performance under water stress or high temperature is one of the possible paths to sustain high-quality viticulture in view of future climate change (Duchêne, 2016). However, this breeding challenge is not trivial for perennial fruit crops, including grapevine, since the main traits targeted for genetic improvement (*e.g.* plant growth and tolerance to abiotic stresses, yield, fruit quality) are quantitative and complex, as they result from many interactions and trade-off between various physiological and molecular processes that (i) act at different temporal, spatial and structural scales and (ii) depend on environmental conditions and management strategies.

Ecophysiological process-based models (PBMs) can predict quantitative traits of one genotype in any environment, whereas quantitative trait locus (QTL) models predict the contribution of alleles under a limited number of environments (Tardieu, 2003). Approaches combining both ecophysiological modeling and QTL analyses have been developed recently (Hammer *et al.*, 2006 ; Reymond *et al.*, 2003 ; Yin *et al.*, 1999), essentially in annual crops, to overcome the strong G×E interactions in the control of complex traits in plants and to improve QTL detection power. The method dissects the genotypic variation of a given complex trait into simpler ecophysiological model parameters linked to key underlying processes involved in this trait. Then, co-localization (or absence thereof) between QTLs for the trait and QTLs for model parameters can give new insights into the contribution of processes involved in the trait.

Hence, it may help in the choice of candidate genes, or may give clues about the genomic regions to be combined in an ideotype. This approach is particularly well suited for studying plant adaptive responses to diverse environmental conditions (Prudent *et al.*, 2011). It appears as a valuable tool to help make informed decisions with regard to genotypic adaptation options and ideotype design in the context of climate change (Ramirez-Villegas *et al.*, 2015).

Such an approach combining ecophysiological modeling and genetic analyses is still in infancy in the international grape community (Duchêne *et al.*, 2012 ; Marguerit *et al.*, 2012). We report here some of the pioneering work from the French LACCAVE research consortium on this topic. Models developed for plant drought response and berry sugar accumulation are outlined. These models consist of simple response curves for one trait or are able to simulate more complex physiological processes. Genetic parameters were defined and their variations among genotypes or segregating populations analyzed. The potential use of such models to simulate grapevine ideotype behavior under future climatic conditions is discussed.

Gene-by-gene breeding approach remains elusive for complex traits in grapes

Over the past century, conventional plant breeding has been used successfully to improve several crops. With the recent progress in molecular technologies for genome sequencing and functional genomics, genes have become tangible rather than virtual entities (Hammer *et al.*, 2006). It is widely anticipated that a gene-by-gene approach will improve plant breeding efficiency. Indeed, there have been successes in developing plants that are more resistant to pests or tolerant to herbicides. Those cases involved single-gene transformations where plant phenotypic response scaled directly from the level of molecular action. However, this has not yet been extended to key complex traits where relationships among components and their genetic control involve quantitative multi-gene interactions (Tardieu, 2003).

In grapes, up to now, few physiological functions have been clearly related to known gene sequences, and the tremendous progress in gene discovery has only weakly aided genetic selection (Martinez-Zapater *et al.*, 2010). This results partly from the complexity of most of the traits of interest and their control by multiple interacting genes, which themselves interact with the environment (Bertin *et al.*, 2010). Therefore, QTLs for a given trait usually explain only a low proportion of the observed trait variations (Fanizza *et al.*, 2005). In addition, as most of these QTLs depend on the environment and the genetic background (Chenu *et al.*, 2009 ; Reymond *et al.*, 2004), extensive experiments over several years at different sites or under different environments have to be performed. Although this approach is useful to evaluate QTL stability (Prudent *et al.*, 2011), it is time-consuming and expensive and can be only conducted with few genotypes and traits (Bertin *et al.*, 2010).

To understand and unravel these Genotype × Environment interactions, the use of PBMs has been proposed (Hammer *et al.*, 2005 ; Yin *et al.*, 2004 ; Yin and Struik, 2016).

Modeling plant responses to future environments is still a challenging issue in grapes

PBMs have been increasingly used in perennial fruit crop research during the last 50 years and are undoubtedly interesting heuristic tools for quantifying plant responses to environmental and management factors within a mathematical framework (Génard *et al.*, 2007 ; Struik *et al.*, 2005). This framework allows dynamic simulations of the main underlying biophysical processes that determine plant growth and development and fruit quality build-up, as well as characterization of the phenotypic plasticity. Environmental factors are often considered as input model-driving variables, and parameters are used to represent genotype-specific characteristics. Phenotypes or traits of interest are the emergent outcomes of the represented system. As PBMs represent causality between component processes, they can predict plant behavior beyond the environment for which model parameters were estimated. This singular property allows the models to potentially resolve G×E interactions into underlying processes and predict plant performance in any environment. As a result, these models can offer significant advantages in assessing and simulating the effects of climate change as compared to purely statistical or rule-based models derived

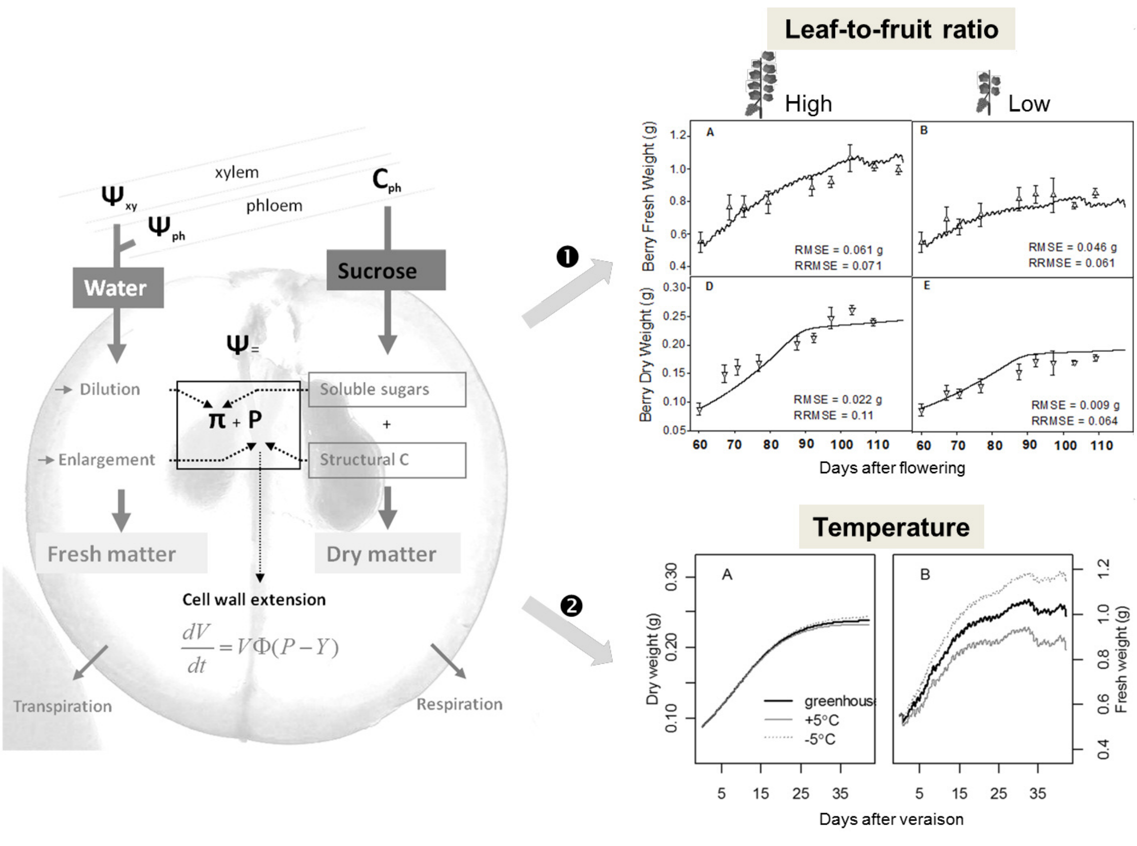

Figure 1 - Modeling the effects of environmental and management practices on dry and fresh mass accumulation in ripening grape berries (adapted from Dai *et al.*, 2008, 2010).
A process-based model was developed to describe the growth of an individual berry on a diurnal basis taking into consideration only fundamental biophysical processes and their response to external conditions. It accurately predicted mean berry fresh and dry mass accumulation in response to different leaf-to-fruit ratios or canopy temperature. Briefly, the model represents a virtual mean berry during the post-veraison developmental stage, which is assumed to behave as a single cell separated by a composite membrane from the parent vine and the outside environment. Water accumulation was calculated through the water balance between xylem and phloem water influx and transpiration water loss, controlled by water potential gradient between the berry and the parent vine. Meanwhile, dry mass accumulation was simulated with the balance between phloem sugar import and respiration carbon depletion. The inputs of the model included initial fresh and dry mass, phloem sugar concentration, xylem water potential, fruit temperature and air humidity.

from previously collected data, which have no explanatory power (Soussana *et al.*, 2010). However, shortcomings exist. Uncertainty in PBM outputs could be higher than for the empirical approach due to greater model parameters and data inputs to represent the many processes in the system (Challinor *et al.*, 2009). The addition of processes and parameters makes it hard to evaluate error propagation and to understand the different sources of uncertainty and their relative importance. Moreover, applied to similar environmental conditions, different models often provide different results (Rötter *et al.*, 2015). Finally, modelers must keep in mind that whatever the level of complexity of PBMs, it will be impossible to reproduce precisely the biological reality and to identify all the factors for all situations that may influence plant performance (Sinclair and Seligman, 1996).

A large diversity of PBMs exists in grape literature (see for review Dai *et al.*, 2010; Moriondo *et al.*, 2015), developed at different time and spatial scales, ranging from crop models, which aim at simulating the entire plant growth cycle (*e.g.* Bindi *et al.*, 1996; Garcia de Cortazar-Atauri *et al.*, 2006), to functional models, which focus more on specific processes such as phenology (Cola *et al.*, 2014; Garcia de Cortazar-Atauri *et al.*, 2009; Parker *et al.*, 2011, 2013), leaf gas exchanges (Prieto *et al.*, 2012), plant water dynamics (Lebon *et al.*, 2003), or berry growth and quality (Dai *et al.*, 2008; **Figure 1**). The choice of which processes to represent in detail and the level of complexity achieved for a given process is of course conditioned by the understanding of underlying grapevine physiology and the available experimental dataset. It is also governed by research focus and intended model use. Therefore, several key processes are still poorly simulated in current grape PBMs. For instance, modeling the distribution of acquired resources among source and sink organs (in particular to the root system) and its plasticity in relation to external availability is one of the weakest features. It is, however, of great importance in plant growth and yield (Vivin *et al.*, 2002). The perennial nature of grapevine is also rarely considered, and the relevant contribution of resource reserves in simulating the plant growth process is not well represented (Moriondo *et al.*, 2015). An understanding of below-ground processes and nutrient assimilation is widely lacking in most models. Concerning yield and fruit quality, models are mainly restricted so far to berry growth, focusing on dry mass accumulation; forthcoming fruit models must now focus on essential aspects of berry composition such as sweetness, acidity, and secondary metabolites (Dai *et al.*, 2010).

Presently, most PBMs account to some degree for the effects of environmental variables and basic plant management. PBMs typically respond to temperature, plant water status, radiation, and atmospheric CO_2 concentration and therefore can be applied to assess impacts of, and adaptation to, future climate projections (Mosedale *et al.*, 2016). However, to deepen this analysis, it is still necessary to enlarge their ability to capture the effects of climatic variability and extremes (Soussana *et al.*, 2010). For example, PBMs often consider the increasing temperature effects on various processes including phenology, carbon uptake and assimilation, and evapotranspiration; however, heat stress impacts or acclimation feedbacks are not considered explicitly, which can generate biased predictions in the models under analysis. Similarly, water and nutrient stresses are typically captured so far by empirical calibration. It is also known that increased CO_2 concentration can limit water loss through stomata; however, many models lack explicit details about photosynthesis and cannot account for the interaction between water use and production (Rötter *et al.*, 2015). As such, they may overemphasize the effects of future droughts. Finally, progress has been made in testing PBMs with field experiments under a wide range of growing conditions, even effects of CO_2 with FACE experiments (Bindi *et al.*, 2001). However, multi-site, multi-year experiments studying the effects of climate change variability are still scarce.

Process-based models could provide a relevant framework for analyzing genetic diversity and enhancing progress in plant breeding

While current PBMs often prove as valuable in guiding research as in providing quantitative predictions, they still lack the ability to describe all the subtle complexities associated with genotypic differences (Yin and Struik, 2008), and only few models incorporate knowledge derived from genomic studies. To become effective tools for addressing G×E interactions, existing models first have to be improved, both in terms of model structure and input parameters (Bertin *et al.*, 2010). Predicting complex traits in relation to G×E interactions requires the design of mechanistic models that represent as much as possible the underlying physiological processes and generate the phenotype of the plant as an emergent consequence of model dynamics (Boote *et al.*, 2001).

A key feature of the models considered is the level of granularity that adequately captures the crucial elements of system dynamics (*i. e.* models should be 'as simple as possible, but not simpler') (Hammer *et al.*, 2006); therefore, much of the fine detail is not required in generating a robust prediction of system behavior (Tardieu, 2010). Secondly, the model equations describing the mechanisms should ideally contain a few genotypic parameters independent of the environment, (i) of which values show a significant range of variation among the studied genotypes and (ii) which have significant influences on model outputs (Bertin *et al.*, 2010), and thus are likely to induce changes in important emergent properties. Model parameters - one set of parameters representing one genotype - must be precisely estimated at low labor cost on a large number of genotypes. They should have a biological meaning, and mutants for parameters should be available to allow the validation of theoretical variations in the models (Bertin *et al.*, 2010). Sensitivity analysis of the model to its parameters can also help in identifying important genotypic parameters and their putative effect under different climates (Quilot *et al.*, 2005). Under these conditions, a robust model provides a dynamic biological framework to analyze component traits. This can generate improved connection to the genetic architecture that controls the trait of interest by identifying model parameters that link more stably to genomic regions than direct phenotypic measures (Tardieu, 2003), as illustrated recently in a tomato sugar model (Prudent *et al.*, 2011).

In grapes, such an approach combining the evaluation of genetic parameters from PBMs and the genetic dissection of the parameters with QTL analyses is scarce. To our knowledge, it has been only successfully applied to quantify the effects of

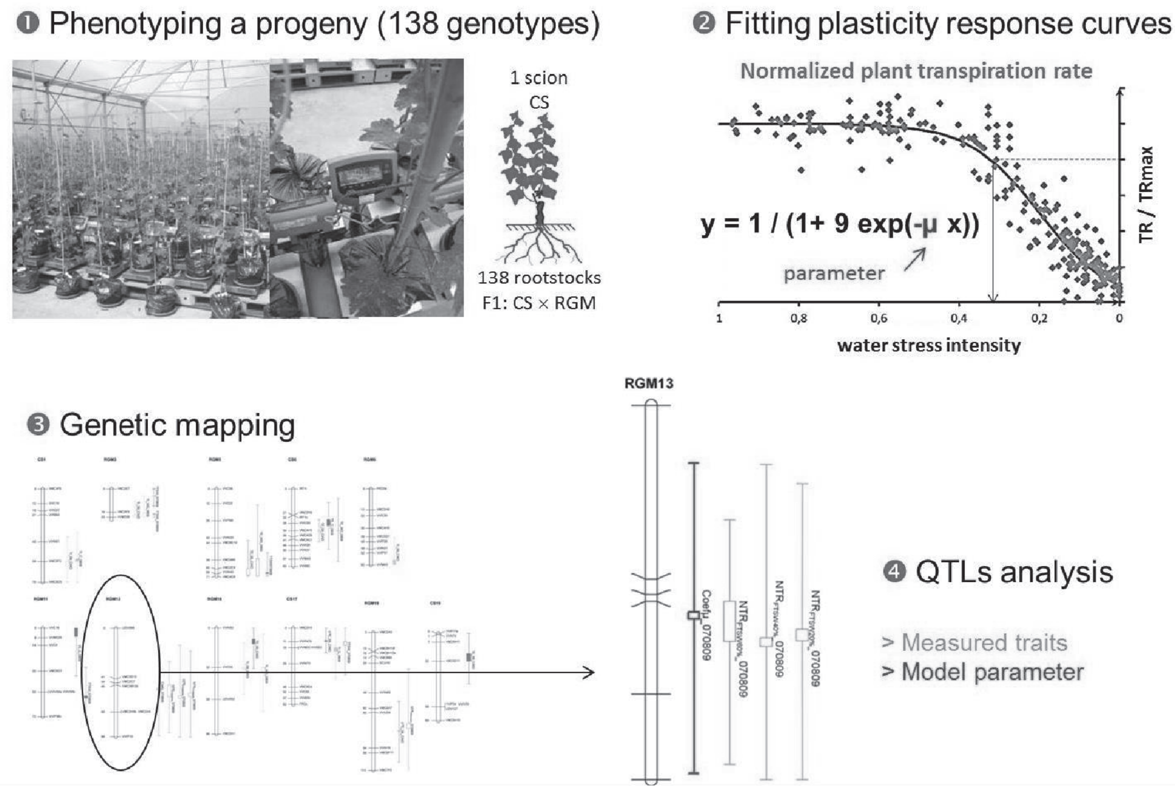

Figure 2 - Diagram of the different steps to identify QTLs of model parameters (adapted from Marguerit *et al.*, 2012). 1) Experimental set-up to control water deficit intensity with balances and to obtain daily transpiration data of 138 genotypes of the mapping pedigree issued from a cross between *Vitis vinifera* Cabernet-Sauvignon and *Vitis riparia* Gloire de Montpellier, 2) Transpiration response curves to water deficit intensity were fitted for all genotypes and each one was characterized by its µ value. Lower µ values were associated with an earlier downregulation of transpiration (in terms of water stress intensity), 3) QTL identification was carried out and genetic maps with QTL localization could be represented, 4) Comparison of the localization of measured traits and model parameter.

allelic variations on parameters of phenological models (Duchêne *et al.*, 2012) and to analyze rootstock control of scion transpiration in response to water deficit (Marguerit *et al.*, 2012 ; **Figure 2**). In both studies, genetic parameters were defined from simple response curves for one trait and their variations among genotypes or *Vitis* segregating populations analyzed. Concerning fruit quality, a PBM predicting post-veraison sugar accumulation in berries was recently developed (Dai *et al.*, 2009) in order (i) to dissect the relative influence of three underlying processes : assimilate supply (S), metabolic transformation of sugars into other compounds (M), and dilution by water uptake (D) ; and (ii) to estimate the genetic variability of S, M, and D. Model analysis over three growing seasons in the progeny from a Riesling × Gewurztraminer cross showed that a coefficient (k) related to the non-sugar use of carbon imported in berries was different between the individuals of the progeny, explaining part of the variability in sugar (Dai *et al.*, 2016). The QTLs linked with this model parameter need to be determined to identify the underlying gene candidates that control the utilization of imported carbon for the non-sugar compounds in grape berry. The combination of physiological observations with model analysis provides an alternative way to identify gene candidates that are involved in berry quality regulation.

Models integrating physiological processes and their genetic control are a first step to design and test *in silico* plants for future environments

A well-defined objective, which describes the desirable features of concerned traits, is a prerequisite for successful breeding programs, including breeding new genotypes specifically adapted to the future environments projected by climate change models. The objective definition process will need first to assess the potential sustainability of the existing genotypes under the future climatic conditions. The next step will be to search by simulation how to combine genetic information to obtain virtual genotypes best adapted to various climatic scenarios (*i. e.* nearest to ideotypes). This process is usually narrowed into mathematical optimization problems to identify the best combinations of genetic parameters values (Quilot-Turion *et al.*, 2012). The feasibility to create the designed cultivar has to be tested by combining PBMs with genetic controls. This is because a virtual cultivar designed without considering the naturally existing genetic variability may not be created in real breeding procedure. In fact, modelers can screen the best allelic combination of genes controlling a given trait through model simulation under a specific environment. However, producing the identified genotype can be easy or difficult depending on the positions of the considered genes and the distance between them, although breeders have developed strategies to separate closely linked genes (Letort *et al.*, 2008). In addition, it is extremely useful to have an idea of the value of a virtual genotype without having really to build it, especially in the case of pleiotropy when compromises have to be made. Using model parameters to build such genotypes should help to overcome the limitations due to environmental pressure on QTL detection. The exploitation of QTLs in breeding programs is, however, conditioned by their heritability, the level of genetic variations in the populations, the genetic correlations among them, and the number of loci related to the trait.

Many PBMs have been used in various crops to conduct *in silico* simulation by integrating the existing genotypes with projected future environments, yet very few studies concerned grapes (Bindi *et al.*, 1996 ; Garcia de Cortazar-Atauri, 2006 ; Fraga *et al.*, 2016). For example, phenology models have been successfully used to test the budbreak, flowering and veraison dates of grapevine cvs. Riesling and Gewurztraminer in the future environment (Duchêne *et al.*, 2010). In this work, the authors also analyzed the genetic variations for the parameters of a temperature-based phenology model among genotypes from the progeny of these two varieties. This allowed the design of virtual genotypes and the testing of their behavior (*i. e.* the calculation of the expected budbreak, flowering and veraison dates), under an IPCC (Intergovernmental panel on climate change) scenario. Doing so can provided clues as to whether existing and virtual genetic variability will be reached to face the extent of predicted climate changes. Similar studies should be developed on more complex adaptive traits in the future.

Conclusions

An approach combining ecophysiological modeling and genetic analyses is original and challenging in grapes in terms of objectives and outcomes. It should provide a promising way of overcoming the uncertainties associated with gene and environment context dependencies that currently impede progress in molecular breeding. Furthermore, it is a first step towards ideotypes for new grapevine cultivars better adapted to future issues of viticulture. A prerequisite is the development of robust PBMs able to describe physiological processes and their responses to variations in environmental conditions and to allow physiological feedback features and the integration of information from different organizational levels. In addition, PBMs will have to be tested for a large set of genotypes in order to extend their ability to simulate genetic variations and identify strong genotypic parameters.

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Severe trimming and enhanced competition of laterals as a tool to delay ripening in Tempranillo vineyards under semiarid conditions

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Abstract

Aim: An advance in grapevine phenological stages (including ripening) is occurring worldwide due to global warming and, in the hottest seasons, already results in a lack of synchrony between sugar and phenolic ripeness, leading to unbalanced wines. In order to cope with this fact, a general effort is being made by researchers and growers aiming at delaying ripening through cultural practices, particularly under warm growing conditions, where these effects are more deleterious. The aim of this work is to evaluate to which extent severe trimming and enhanced competition of laterals can delay ripening in Tempranillo vineyards under semiarid conditions.

Methods and results: The experiment took place during two consecutive seasons in Traibuenas (Navarra, Spain) in a cv. 'Tempranillo' vineyard trained to a vertical shoot positioned (VSP) spur-pruned bilateral cordon. Severe mechanical pruning was performed ca. 3 weeks after fruit-set in order to reduce leaf-to-fruit ratio, and in the trimmed plants, three irrigation doses were applied until harvest aiming at enhancing lateral growth, hypothesized to compete with ripening. All measurements were performed in six 10-vine replicates per treatment. Trimming significantly reduced leaf area and yield, resulting in higher water availability in trimmed plants. The whole ripening process was delayed by trimming: mid-veraison was delayed by about 5 days, and the delay in sugar accumulation and acid degradation was longer, differences being more marked in malic than in tartaric acid concentration. The use of increased irrigation levels compensated the losses in yield caused by trimming, enhanced laterals' growth and implied an additional delay in ripening.

Conclusion: trimming and increased irrigation had an additive effect in terms of delaying ripening, and they can be used jointly when that delay is needed.

Significance and impact of the study: this study proves the potentiality of the joint use of trimming and increased irrigation to delay ripening, although it is necessary to analyze the implications the obtained delay has on other quality aspects. The lower anthocyanin and phenolic values observed in trimmed vines were not solely due to delayed ripening, as lower values were observed even when data were compared for a given total soluble solid content.

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Introduction

Adaptation to climate change is a major challenge for the wine grape growing sector, since climatic conditions affect not only the crop's sustainability, but also its *typicity*, i.e. the specific characteristics that make a wine produced in a given region or terroir singular. During the last decades, most of the world's highest quality wine-producing regions have shown a warming trend during the growing season (Duchêne and Schneider, 2005; Jones *et al.*, 2005). This change has led to an advance in phenology, which, jointly with some changes in cultural practices, resulted in earlier harvest dates, higher sugar concentration in grapes, and higher alcoholic concentration in wines (Duchêne and Schneider, 2005; Ramos *et al.*, 2008; Tomasi *et al.*, 2011; Neethling *et al.*, 2012; Webb *et al.*, 2012; Bock *et al.*, 2013; Koufos *et al.*, 2014; van Leeuwen and Darriet, 2016). Higher berry sugar content usually implies higher must pH, which results in less stable, less colored, leaner wines (Ribéreau-Gayon *et al.*, 2000).

Moreover, advanced phenology indirectly implies that physiological ripening processes are occurring at increased temperatures, which can have a direct impact on grape composition (Keller, 2010). With regards to aromatic compounds, several studies suggested that, at equivalent sugar concentrations, higher temperatures lead to lower levels in white aromatic grape varietals, thus potentially reducing aromatic intensity (Mira de Orduña, 2010). In red grape varieties, high temperatures during ripening have also been shown to decouple sugar and phenolic maturity (Sadras and Moran, 2012; Bonada *et al.*, 2013; Teixeira *et al.*, 2013), resulting in altered organoleptic profiles.

Although climate change can favor grape growing in some regions (Fraga *et al.*, 2012; Hannah *et al.*, 2013), this is not the case for most wine regions in Spain and Portugal, where climatic change can negatively impact grape growing (Malheiro *et al.*, 2012; Resco, 2015; Lorenzo *et al.*, 2016). The change in climatic conditions during the last decades is a matter of fact. For instance, in La Rioja and Navarra, two wine regions in Northern Spain, all bioclimatic indices relevant to viticulture have changed significantly between 1951-1980 and 1981-2010 (Figure 1). As a consequence, the abovementioned detrimental effects of advanced ripening on grape and wine composition are becoming an increasing problem that needs to be addressed (Alonso and O'Neill, 2011; Martinez de Toda *et al.*, 2014).

Looking at the past to understand the future

When facing a new climatic scenario, winegrowers can display a wide set of cultural techniques in order to minimize its effects (Neethling *et al.*, 2016). Among them, adapting the training systems and canopy management operations, planting vineyards at higher altitudes, and changing vinifera/rootstock varieties and soil management practices can be regarded as the most powerful tools (Battaglini *et al.*, 2009; Duchêne *et al.*, 2010; Neethling *et al.*, 2016). However, some of the changes made in Navarra and Rioja (and in many other areas in Spain) in the past decades (particularly in the 1980-2000 period) have led to a certain degree of *miss-adaptation* to climate change, despite being associated to the introduction of irrigation:

Table 1. Effect of trimming and irrigation treatments on trunk cross sectional area (TCSA), shoot characteristics, cluster number, yield and carbon isotope ratio ($\delta^{13}C$)

Treatment	TCSA (cm^2 $vine^{-1}$	Main shoot length (cm)*	No. laterals main shoot $^{-1}$	Total lateral length (cm $shoot^{-1}$)	Cluster number $vine^{-1}$	Yield (kg vine-1	$\delta^{13}C$ (‰)
Control	18.3	83.4 a	1.20 b	12.6 c	12.1	2.73 ab	-25.18 a
Trim + R1	18.2	56.7 b	1.41 ab	19.2 c	10.8	2.36 b	-25.97 b
Trim + R2	17.9	58.4 b	1.43 ab	36.4 b	11.0	2.57 ab	-26.94 c
Trim + R3	18.2	61.9 b	1.57 a	49.7 a	11.5	2.98 a	-27.44 d
P	*0.844*	*<0.001*	*0.016*	*<0.001*	*0.474*	*0.032*	*<0.001*
Year							
2014	17.7	--	--	--	11.3	2.24	-26.01
2015	18.7	--	--	--	11.6	3.09	-26.75
P	*0.005*	--	--	--	*0.583*	*<0.001*	*0.013*
Interaction							
P_{int}	*0.924*	--	--	--	*0.975*	*0.648*	*0.205*

*main shoot length, no. laterals and total lateral length were measured only in 2015; data were analyzed through a one-way ANOVA

- (i) New vineyards were frequently planted in irrigated areas, moving from poor but deep soils to more fertile but shallower soils, where irrigation water was available. When the maps of vineyard locations in Navarra in 1956 and 2012 are compared (Figure 2), it can be seen that the altitude of vineyards has changed significantly (Figure 3). At a regional level, the decrease accounts for 20 m, with a particularly important change (18 m) in the warmest sub-area (zone VII).

- (ii) In addition to location change, the traditional low-water-consuming gobelet training system was shifted to vertical shoot positioned (VSP) systems

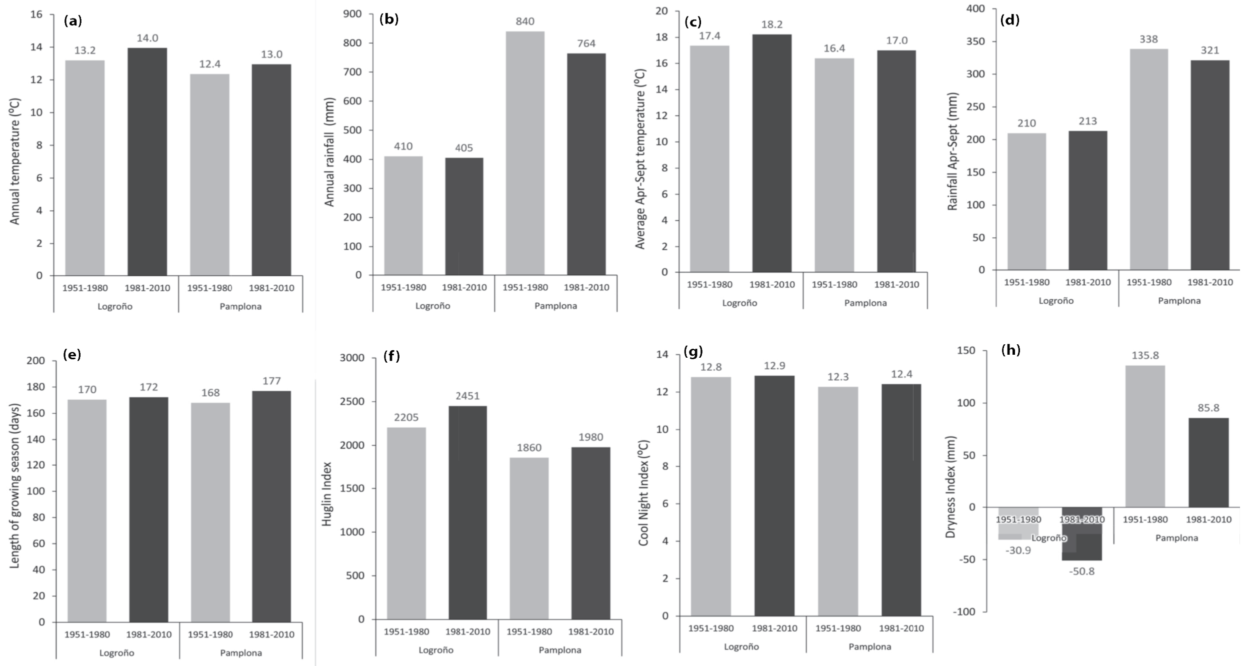

Figure 1. Comparison of bioclimatic indices for the 1951-1980 and 1981-2010 periods at Logroño-Agoncillo (La Rioja) and Pamplona (Navarra) observatories. Elaborated using the Daily Dataset for European Climate Assessment (Klein Tank *et al.*, 2002) available at http://www.ecad.eu.

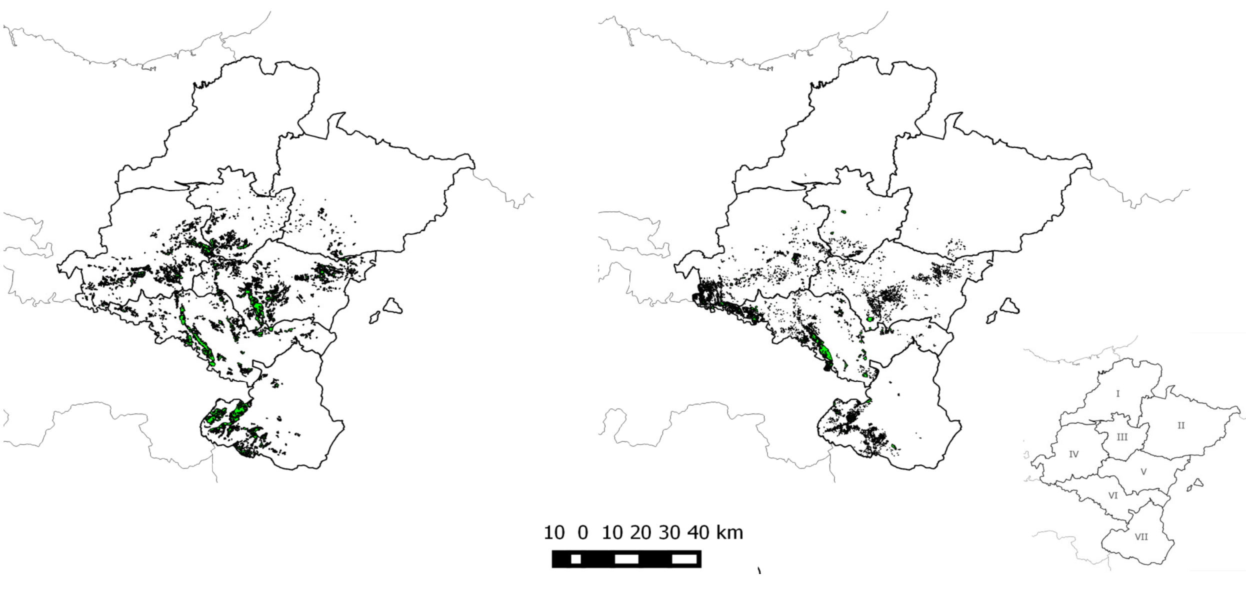

Figure 2. Comparison of the 1956 (left) and 2012 (right) land use maps of Navarre; agricultural areas are indicated as roman numbers. Elaborated using data provided by Navarre Territorial Information System (SITNA) distributed under Creative Commons Licence at http://idena.navarra.es/.

where, apart from the increased water needs (Reynolds and Heuvel, 2009), clusters are much more exposed to solar radiation and therefore subjected to higher temperatures.

(iii) Last, there was a varietal shift from Grenache N to Tempranillo (Figure 4), tolerant and sensitive to water deficit, respectively (Santesteban *et al.*, 2009; Martorell *et al.*, 2015), with the former tending to give lower pH juices than the latter (Garcia *et al.*, 2011). Tempranillo, as an autochthonous variety, is well adapted to its original habitat (i.e. the cooler areas in Rioja), but during this varietal shift, it was also used for planting most vineyards in the warmest areas of the region.

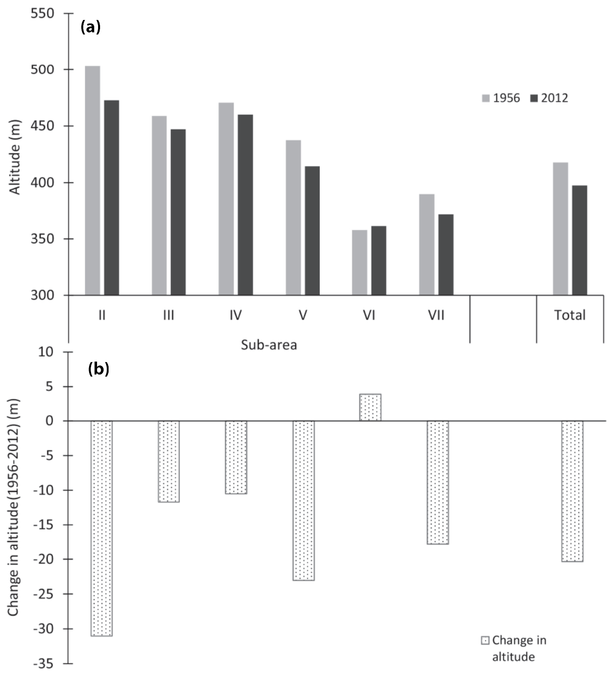

Figure 3. Mean altitude of vineyards in Navarra agricultural areas in 1956 and 2012 (a) and altitude change in that period (b). Agricultural areas correspond to those indicated in Figure 2. Elaborated from land use maps and terrain elevation models provided by Navarre Territorial Information System (SITNA, http://idena.navarra.es/) using QGIS 2.12. and GRASS open access software packages.

Although the introduction of irrigation made it possible for vineyards to be located in shallower soils (using a more drought-sensitive cultivar with a more water-demanding training system), other side-effects appeared, like unwanted high sugar and pH values, berry shriveling and uncoupled sugar and phenolic ripening. In this context, a reversion of the variety change is starting to be implemented, with the growing presence of the low pH, high color cv. Graciano for blending. A big effort is also being made to find cultural practices that can help the growers to adapt to climate change (Martínez de Toda and Balda, 2013; Martinez de Toda *et al.*, 2013; Martinez de Toda *et al.*, 2014).

The aim of this work is to evaluate to which extent severe trimming and enhanced competition of laterals can delay ripening in Tempranillo vineyards under semiarid conditions.

Materials and Methods

1. Experimental design

The experiment took place during the 2014 and 2015 growing seasons in Traibuenas (Navarra, Spain) in a 4.2 ha 'Tempranillo'/110 Richter vineyard (42º 23' 7'' N, 1º 37' 29'' W, 350 m a.s.l.). Vines were 17

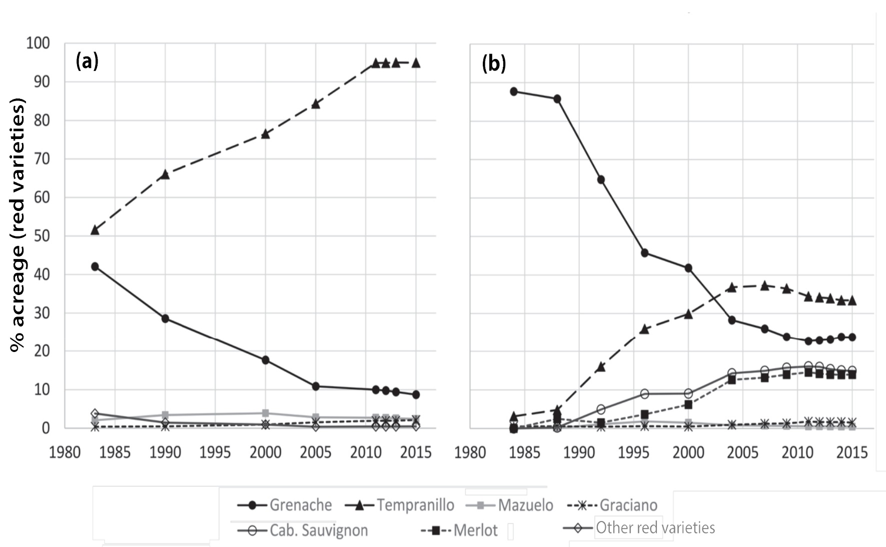

Figure 4. Evolution of the relative acreage of the red varieties grown in AO Rioja (a) and in AO Navarra (b) in the 1983-2015 period. Data were provided by the Regulatory Boards of both AO.

years old at the beginning of the experiment, planted at 3 x 1 m spacing, and trained to a VSP spur-pruned bilateral cordon, with three 2-bud spurs per arm.

Control vines (CTRL) were subjected to standard practices and compared to three treatments. In all treatments, severe mechanical trimming (TRIM) was performed ca. 3 weeks after fruit-set (pea-size) by cutting shoots at ca. 55-65 cm. The trimmed treatments differed in the irrigation level: Trim+R1 plants received the same amount of water than control plants (ca. 36 L vine^{-1} once a week from pea-size to harvest), whereas Trim+R2 and Trim+R3 plants were irrigated two and three times a week for 4-5 weeks after trimming (ca. 72 and 108 L vine^{-1} every week, respectively). None of the treatments was irrigated between harvest and pea-size. The hypothesis supporting this approach is that reduced leaf-to-fruit ratio and enhanced lateral shoot growth can delay ripening through, respectively, decreased leaf-to-fruit ratio and increased competition. The experimental layout was set-up at a nearly commercial scale (2.4 ha of vines as a whole), measurements being taken in six 10-vine replicates per treatment.

2. Measured variables

In winter, trunk cross sectional area (TCSA) was calculated after measuring trunk diameter 30 cm above-ground, and total shoot growth determined measuring main shoot length, the number of laterals, and lateral's length (only in 2015). Veraison was determined by careful visual inspection of 30 clusters per replicate twice a week from the onset until the end of veraison.

Yield was determined at harvest by counting and weighing all the clusters produced in the 10 vines in each replicate. Grape composition was determined weekly between veraison and harvest in one 300-berry sample per replicate. Samples were processed according to standard laboratory procedures in order to determine berry weight (BW), total soluble solids (TSS), pH, titratable acidity (TA), and malic (MalA) and tartaric (TarA) acid concentration. Phenolic ripeness was evaluated using the Cromoenos® method (Bioenos, Cariñena, Spain, http://www.bioenos.com/cromoenos/index.php), which allows determining total anthocyanins (TAnt), total phenolics (TP), and a phenolic maturity index (PMI) after a fast extraction in buffer solutions.

Plant water status was monitored weekly between fruit-set and harvest. Stem water potential at midday (Ψ_{midday}) was determined for three healthy leaves per replicate, bagged 1.5 hours prior to measurement using zip-bags covered with a metalized high-density polyethylene reflective film. Measurements were carried out with a Scholander pressure bomb (P3000, Soil Moisture Corp., Santa Barbara, CA, USA). Finally, berry carbon isotope ratio ($\delta^{13}C$) was determined in 50-berry samples collected at harvest, oven-dried, ground into a fine homogeneous powder, and analyzed using an Elemental analyzer (NC2500, Carlo Erba Reagents, Rodano, Italy) coupled to an Isotopic Mass Spectrometer (Thermoquest Delta Plus, ThermoFinnigan, Bremen, Germany) as detailed in Santesteban *et al.* (2012).

3. Data analysis

Data were analyzed using linear regression and two-way ANOVA (trimming/irrigation treatment x season). All analyses were performed with computing environment R (R Development Core Team, 2015).

Results

1. Vegetative growth and yield

Both trimming and additional irrigation achieved their goal in terms of vegetative growth (Table 1). Trimming caused a significant decrease in main shoot length and a slight increase in the number of laterals, whereas increased irrigation resulted in longer laterals. Trimming significantly decreased yield, but this was compensated by the increased irrigation treatments.

2. Plant water status

The evolution of water status followed a similar pattern in both years (Figure 5), with slightly lower midday stem water potential values in 2015. Increased irrigation resulted, as expected, in higher stem water potential, with a clear gradation between Trim+R1, Trim+R2 and Trim+R3 treatments; the same trend was observed when carbon isotope ratio values ($\delta^{13}C$) were compared (Table 1). Trimming also had a relevant effect on vine water status since Trim+R1 plants showed higher water potential and lower $\delta^{13}C$ than control plants, indicating that trimming alleviated to a certain extent the water deficit.

3. Ripening dynamics

Trimming and increased irrigation caused a delay in veraison in both years (Figure 6). In 2014, trimming caused the greatest differences, inducing a 4-day delay in mid-veraison, whereas increased irrigation delayed it an additional day. In 2015, a greater delay was observed, with four days due to trimming, and an additional three days after increased irrigation.

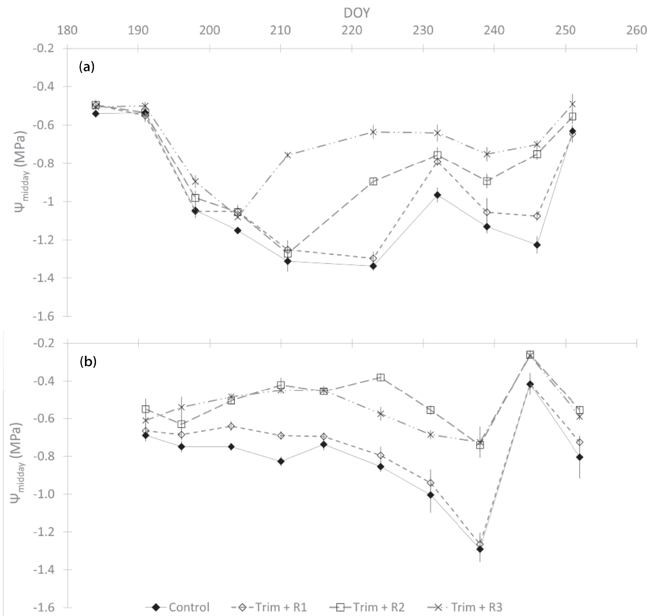

Figure 5. Evolution of stem water potential at midday (Ψ_{midday}) in 2014 (a) and in 2015 (b).

Treatments also affected berry size and ripening dynamics (Figures 7, 8 and 9). Control vines produced smaller berries in both years, and irrigation increased berry size (Figure 7a, c). Both trimming and increased irrigation caused a remarkable delay in sugar content (Figure 7b, d). If we take 23.5 ºBrix as a reference value, trimming resulted in a 9- and 10-day delay in 2014 and 2015, respectively, while increased irrigation additionaly induced 5 days of delay in 2014 and 7 in 2015.. These changes in ripening dynamics were also reflected in acidity parameters (Figure 8): untrimmed vines tended to have an advanced ripening, whereas increased irrigation resulted in an additional delay, showing higher titratable acidity and malic and tartaric concentration, and lower pH for a given date. Last, with regards to phenolic compounds, no clear trends were observed in 2014 (only three sampling dates are available), whereas in 2015 the effects of trimming and increased irrigation were much clearer (Figure 9). On the one side, trimmed vines showed lower anthocyanin and phenolic concentration, and lower PMI values, indicating an advance in phenolic maturity. On the other side, increased irrigation tended to cause lower anthocyanin and phenolic content, and increased PMI values, indicating a delay in ripening.

Discussion

Trimming and additional irrigation induced significant changes in ripening dynamics, resulting in a later onset of ripening and delayed maturity, proving the soundness of our hypothesis. The effect

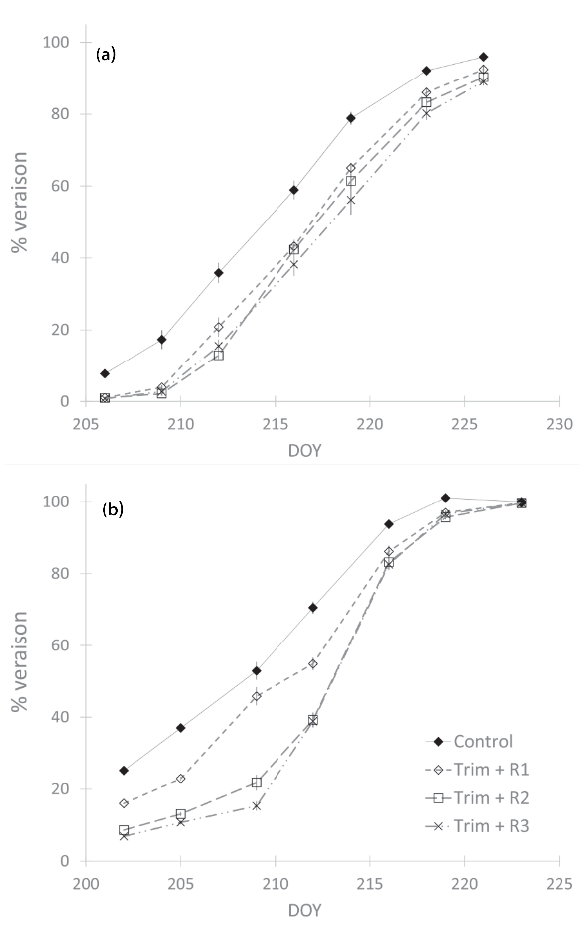

Figure 6. Evolution of veraison percentage in 2014 (a) and in 2015 (b).

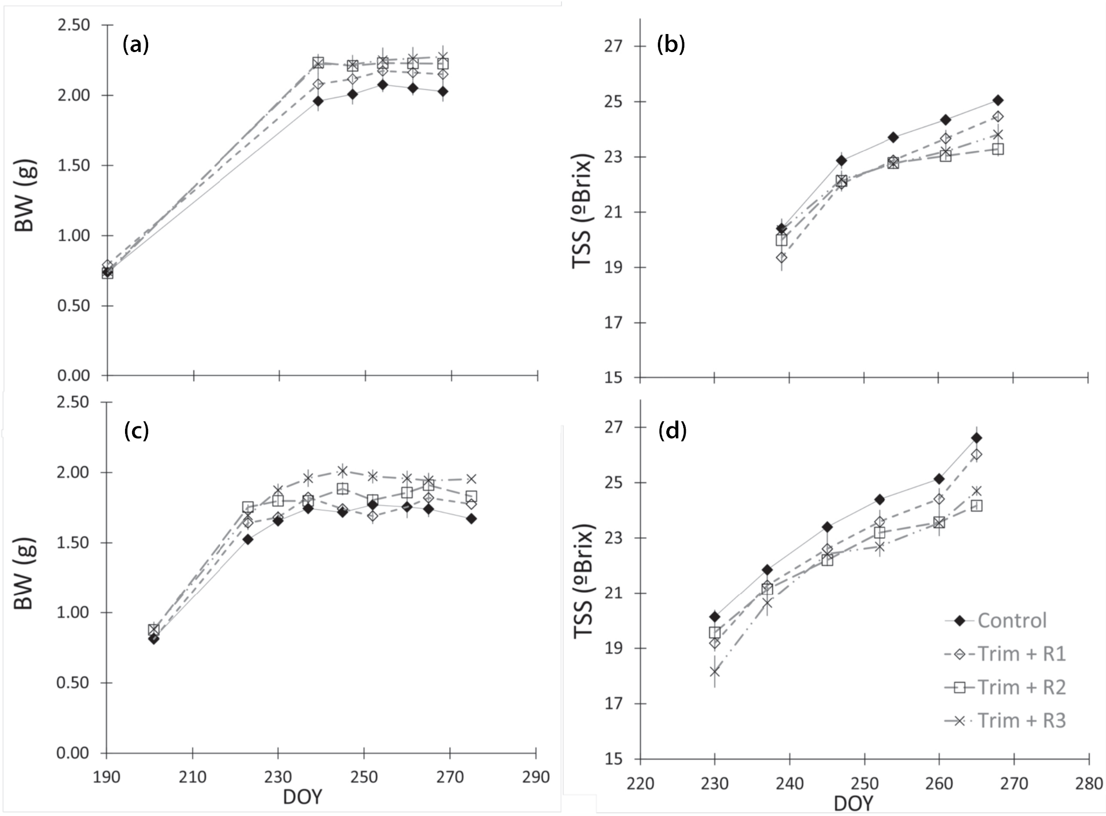

Figure 7. Berry weight (BW) and total soluble solid content (TSS) evolution in 2014 (a, b) and in 2015 (c, d).

of trimming (estimated as a 5-7-day delay) can be explained by a reduced leaf-to-fruit ratio, which, as proved by earlier research, limits plant photosynthesis (Keller *et al.*, 2005; Poni *et al.*, 2013). As a result, yield was also decreased, not due to a reduced berry size, but rather to a lower berry number. Trimming can cause some damage in clusters and, in the second season, decrease cluster and flower differentiation due to an unfavorable carbon balance (Santesteban *et al.*, 2011a; Dayer *et al.*, 2013; Intrigliolo *et al.*, 2016). In fact, the berries of trimmed plants were bigger, probably as a consequence of a lower fruit load and higher plant water availability. Reduced leaf area can certainly decrease water use, especially in cvs. such as 'Tempranillo', known to have poor stomatal control and relatively high night transpiration. However, it should be taken into account that under non-limiting solar radiation latitudes, leaf-to-fruit ratio plays a relatively limited role in carbon balance (Santesteban and Royo, 2006). Wounds resulting from trimming are known to promote a complex response in plants (Schilmiller and Howe, 2005; Delano-Frier *et al.*, 2013; Böttcher *et al.*, 2015). In grapevines, trimming has been shown to modify root hydraulic conductivity through aquaporins and interfere with the normal signaling process (Vandeleur *et al.*, 2014) and could therefore be a factor enhancing stomatal control.

The use of additional irrigation increased the delaying effect of trimming. This delay can be assumed to be due to the enhanced competition of laterals, since higher water availability does not induce by itself a delayed ripening in warm climates, but rather promotes sugar accumulation (Santesteban and Royo, 2006; Chaves *et al.*, 2007; Valdes *et al.*, 2009). The enhanced growth of laterals could be the cause of the higher malic acid content observed, as higher leaf area in the cluster zone reduces cluster temperature (data not shown), which in turn decreases malic acid degradation. However, this does not explain the delayed sugar accumulation in 'trimmed + supplementary irrigation' vines. The observed delay in ripening cannot be due to increased yield, which is known to delay sugar accumulation (Bravdo *et al.*, 1985; Santesteban *et al.*, 2011b), since the yield in Trim+R2 plants was similar to that in control vines, and the delay was remarkable. In all, our results show the potential of lateral growth-promoting techniques as a tool to delay ripening and to adapt to climate change. The originality of our approach is that

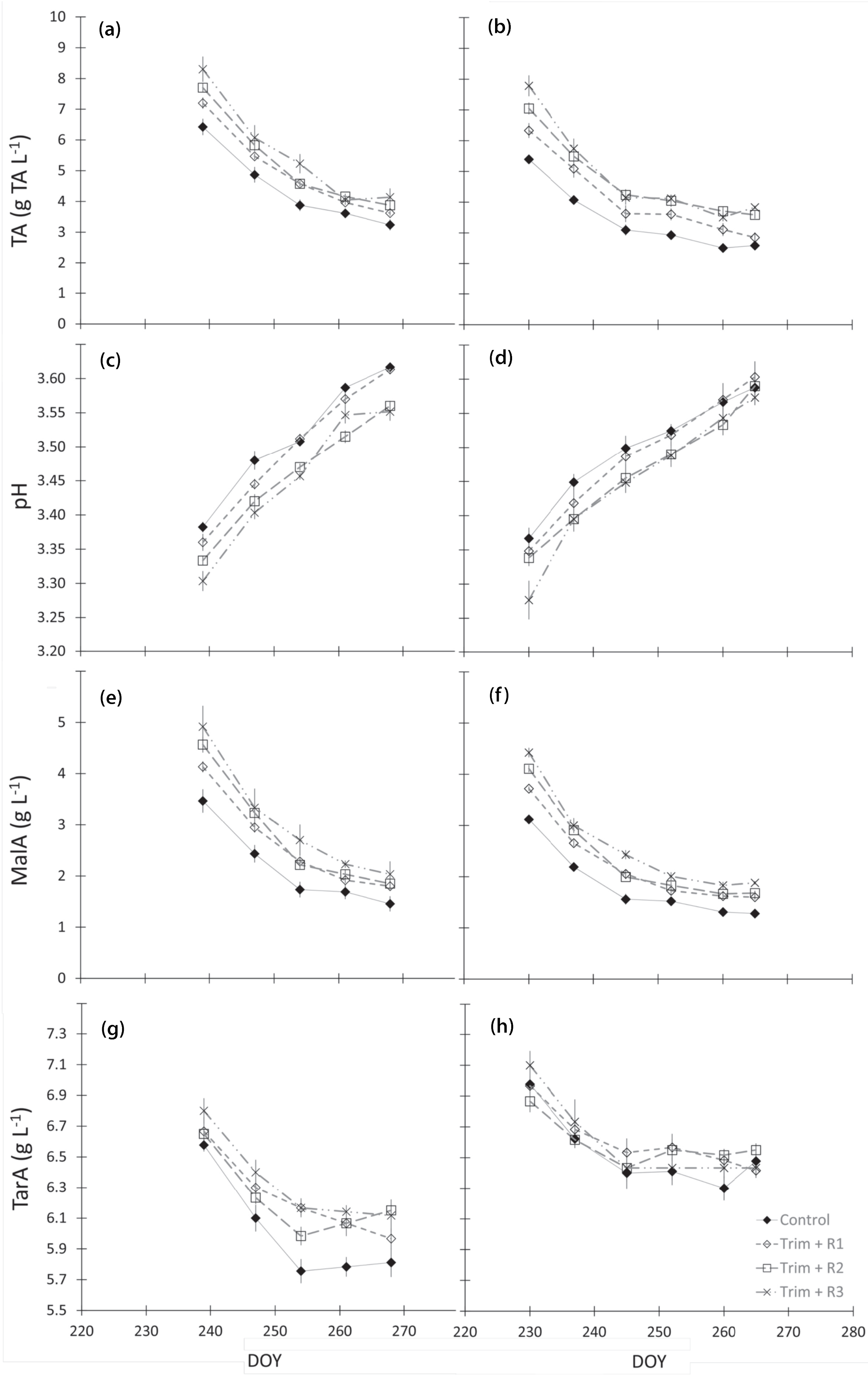

Figure 8. Titratable acidity (TA), pH, and malic (MalA) and tartaric (TarA) concentration evolution in 2014 (a, c, e, g) and in 2015 (b, d, f, h).

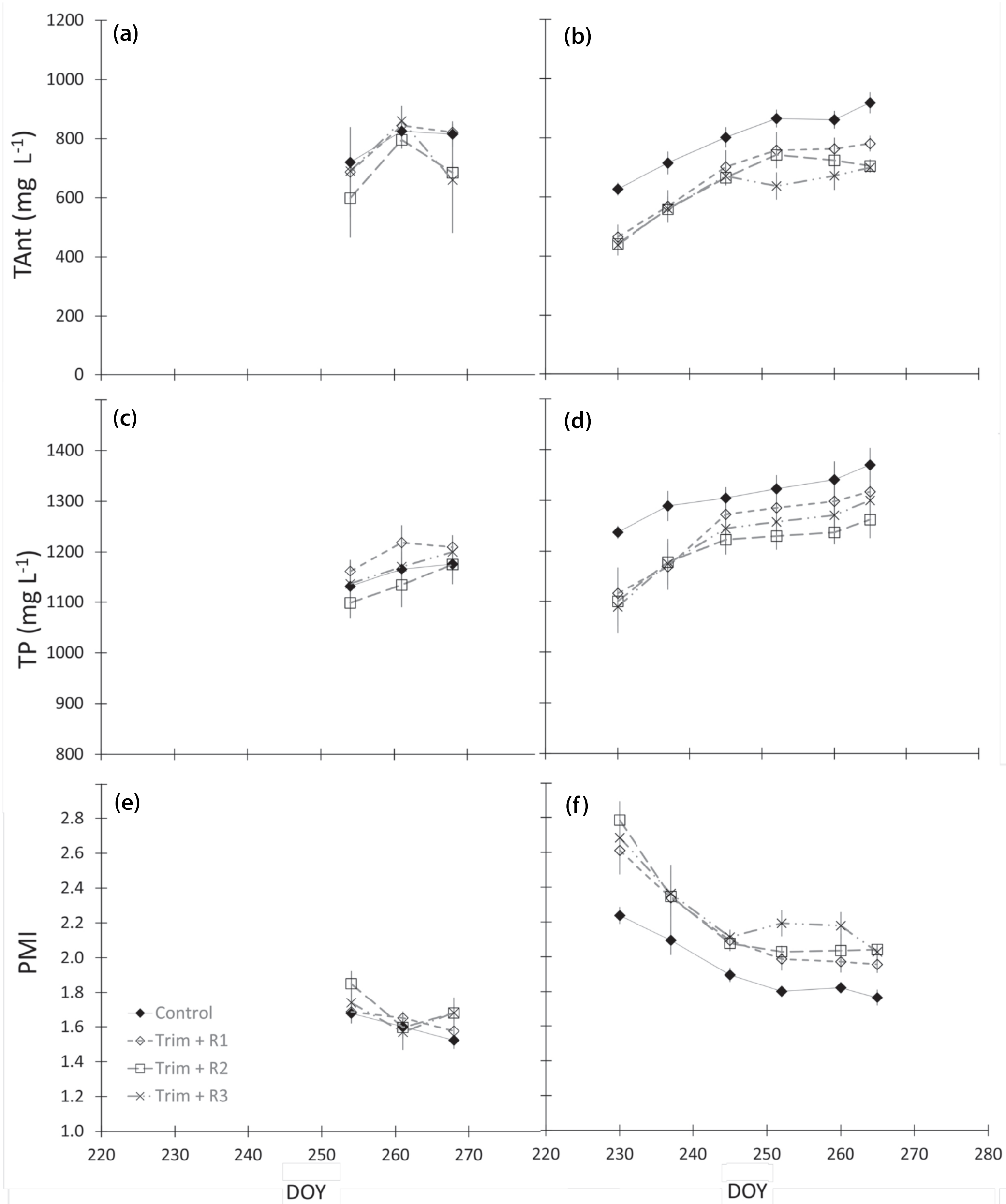

Figure 9. Total anthocyanins (TAnt), total phenolics (TP) and phenolic maturity index (PMI) evolution in 2014 (a, c, e) and in 2015 (b, d, f).

reduced leaf area was combined with enhanced lateral growth.

The results obtained are globally satisfactory since the techniques tested were able to delay ripening. However, it is necessary to test to which extent the effects on ripening balance are favorable from an enological point of view. According to berry ripening dynamics summarized in Figures 8 and 9, berries from trimmed and supplementary irrigated vines had, for a given date, lower sugar content, higher acidity and lower anthocyanin and phenolic content, which can be due to delayed ripening but also to changes in ripening balance. In fact, when we plot grape composition variables against soluble solid content (Figure 10), it can be seen that for a given TSS value, control vines had similar pH, lower titratable and malic acidity, higher anthocyanin content and better phenolic maturity (lower PMI values). Thus, apart from delaying ripening, trimming and trimming + supplemental irrigation intrinsically increased acidity (due to reduced malic degradation), reduced anthocyanin content and resulted in grapes with lower phenolic ripeness. Therefore, it is necessary to be cautious before implementing these techniques at

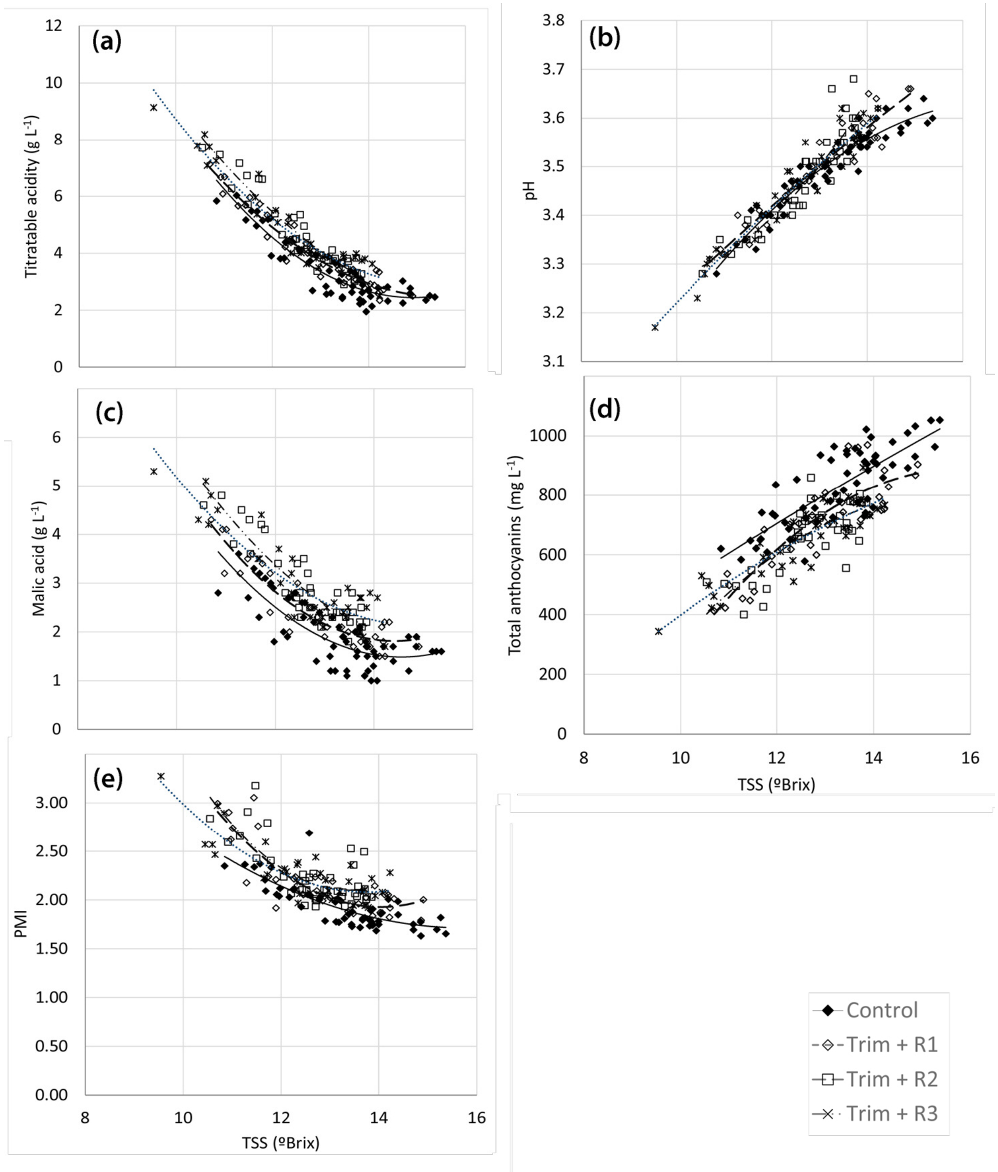

Figure 10. Comparison of total soluble solid content (TSS) and (a) titratable acidity, (b) pH, (c) malic acid, (d) total anthocyanins, and (e) phenolic maturity index (PMI).

a commercial scale. The most positive effect of trimming and increased irrigation is that delayed ripening would allow full ripening under cooler temperatures, more favorable for aroma and phenolic synthesis (Mira de Orduña, 2010). However, if its use implies a decreased anthocyanin and phenolic accumulation, its introduction would not be justified. Besides, in some areas it may not be possible to increase irrigation level (even for a few weeks) due to water scarcity. It is therefore necessary to test the implications of these techniques on the composition and organoleptic properties of the wines produced prior to making any specific recommendation to growers.

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Precision irrigation of grapevines: methods, tools and strategies to maximize the quality and yield of the harvest while conserving water in a context of climate change. Consumer perception

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Abstract

Vineyard irrigation has been used for a very long time in the so-called « new world vineyards » and is widely practiced. Its adoption in the French Mediterranean regions is much more recent and is one of the first techniques adopted by the vine growers to overcome severe drought effects on yield and fruit composition. It is a practice that allows the maintenance of both the quality and quantity of the crop. Irrigation control is based on the characterization of vine water status and on the knowledge of plant response to water deficit according to phenological stage. This knowledge helps in defining an irrigation strategy adapted to the vineyard target (grape juice, white wines, red wines, wines for aging, etc.). However, irrigation may raise several concerns. In this sense, the perception of irrigation practices by wine consumers in a context of climate change is analyzed.

Keywords: grapevine, water deficit, irrigation, quality, yields

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Vine and water

Worldwide, grapevines are grown in areas where the water regime highly depends on the climate (rainfall and evapotranspiration) and soil type (water holding capacity). In several wine producing regions of Australia, Argentina, the United States (California) and Chile, irrigation is a cultivation technique like any other, increasingly used to manage the performance and quality of grapes and wines. In all these countries called « new wine world », irrigated vineyard area reaches 580,000 ha, i. e. approximately 83 % of the total vineyard area. In Argentina, the entire wine-growing area is irrigated (205,000 ha).

In southern France, vineyard irrigation has been a reality since the early 2000s. Languedoc-Roussillon is the main irrigated area in France with 26,000 ha (11 % of the vineyard area), followed by the PACA region with 10,000 ha of irrigated vines[1]. In the Mediterranean area, the consumption of irrigation water is estimated between 0 and 60 mm (0 to 600 m^3/ha/year) depending on the soil, the mesoclimate and the year (Gaudin and Gary, 2012). The surface of irrigated vineyards is increasing because of drought problems and reduced yield inducing a shortage of wines. Indeed, the rise in average temperatures, concomitant with a significant increase in evapotranspiration, generates increased water requirements during the growing cycle. Because precipitations do not increase in proportion to water need, grapevines may face an early water deficit and severe water deficit (Figure 1). This situation requires an adaptation of cultural techniques for Mediterranean vineyards.

However, in the context of climate change, water resources may become limiting and restrictive water management policies will probably emerged. In addition, irrigation may present some limitations, such as the cost of equipments and infrastructures required to provide water to the vineyard. Finally, irrigation may induce salinization of soils with serious risk to the suitability of some area to grow grapes. Consequently, irrigation should be used with caution.

In this context, a rational irrigation management should be based on a quantitative analysis of water needs taking into account soil and climatic characteristics of the plots. Irrigation strategies (demand) have to be adapted to a given production target (quantity and quality linked to the availability) (Figure 2).

The control of irrigation in order to regulate the yield and reach a targeted fruit composition becomes a constant concern of growers. Therefore, more reliable and powerful decision support tools are required to manage the water status of the vine.

Water status and impact on vine

Irrigation is a major agronomic practice to control vineyard water status according to the plot characteristics and production goals (Ojeda, 2007, 2008). However, for an accurate management of this practice, it is necessary to know how the vines

[1]Source AIRMF Association des Irrigants des Régions Méditerranéennes Françaises

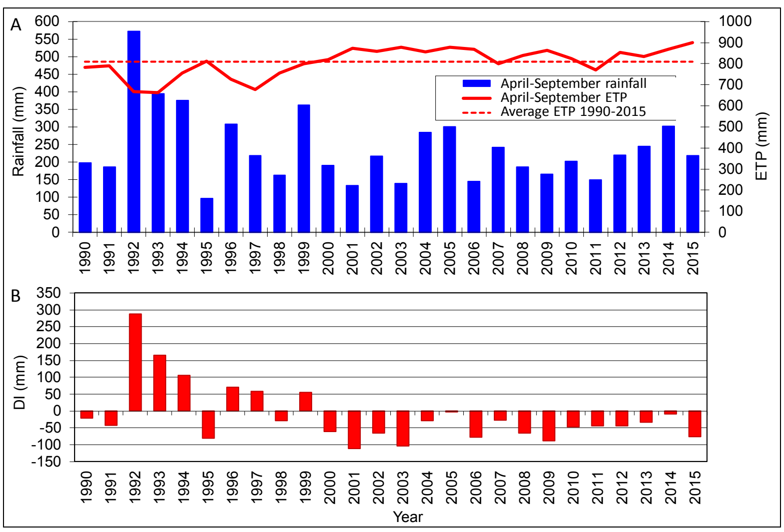

Figure 1. A: Precipitation and evapotranspiration (ETP) fluctuations; B: Dryness Index (DI, Tonietto and Carbonneau, 2004). Period 1990-2015. INRA, Unité Expérimentale de Pech Rouge, Gruissan, France.

respond to water stress according to their phenological stages.

During the period from bud burst to flowering, shoot growth is a priority. Vegetative growth is very sensitive to water deficit. Shoot growth decreases or stops at a relatively low stress level, which does not affect physiological parameters such as photosynthesis and transpiration (Williams *et al.*, 1994; Pellegrino *et al.*, 2006). Therefore, at this stage, a major water deficit should be avoided in order to maintain shoot growth and leaf area development through an adequate supply of water by the roots.

Between fruit set and veraison, the water status has a strong influence on yield through the effect on berry size (Becker and Zimmermann, 1984; McCarthy, 1997; Ojeda *et al.*, 2001). The controlled reduction of berry size can be targeted considering that it determines the skin to pulp ratio and consequently the dilution of specific constituents from the skin, including phenols and aroma precursors, in juice (Singleton, 1972; Cordonnier, 1976; Ojeda *et al.*, 2002). Mineral nutrition may also be affected if drought is severe during this period when the consumption of nitrogen, potassium, phosphorus, and calcium is maximal (Fregoni, 1999). Indeed, nutrient uptake occurs correctly only if minerals are diluted in a soil solution easily available to the roots (Keller, 2005).

The absence of water deficit during grape ripening from veraison to harvest usually promotes high yields. Qualitative components such as polyphenols and sugars are diluted by the effect of increasing berry size (Ojeda *et al.*, 2002). Therefore, this situation should be avoided for the production of quality wines. However, it is suitable for other production targets such as table grapes, concentrated must or grape juice.

A progressive water deficit during the ripening period may limit berry size, and therefore yield. It favors the accumulation of phenolic compounds, predominantly anthocyanins (Ojeda *et al.*, 2002; Berdeja *et al.*, 2014). Stimulation of the secondary metabolism is also associated. However, the optimal water status thresholds are likely to be different for polyphenols or aroma precursors. Some aroma precursors are more susceptible than phenols to high water deficit (Peyrot des Gachons *et al.*, 2005; Tejerina *et al.*, 2013). Consequently, it is probably better to limit water deficit to produce wines, especially white ones, with a high aroma potential.

During the veraison-harvest period, vineyard water status largely determines the type of wine produced (Deloire *et al.*, 2005). In case of total absence of water deficit, it produces herbaceous, diluted and acid wines. In the case of a very severe water stress, red wines are overly tannic, hard, astringent and alcoholic, while white ones have lost much of their aromas.

After harvest, an unconstrained water status will promote carbon allocation to permanent structures (roots, trunk and shoots) (Champagnol, 1984) and increase mineral absorption (Conradie, 2005). In some cases, the production of new roots will resume (Freeman and Smart, 1976; Van Zyl, 1984).

To summarize, during the grape ripening period, the amount of quality-related components (phenols, aroma precursors, sugars, etc.) increases as the water deficit levels rise, although a yield reduction may

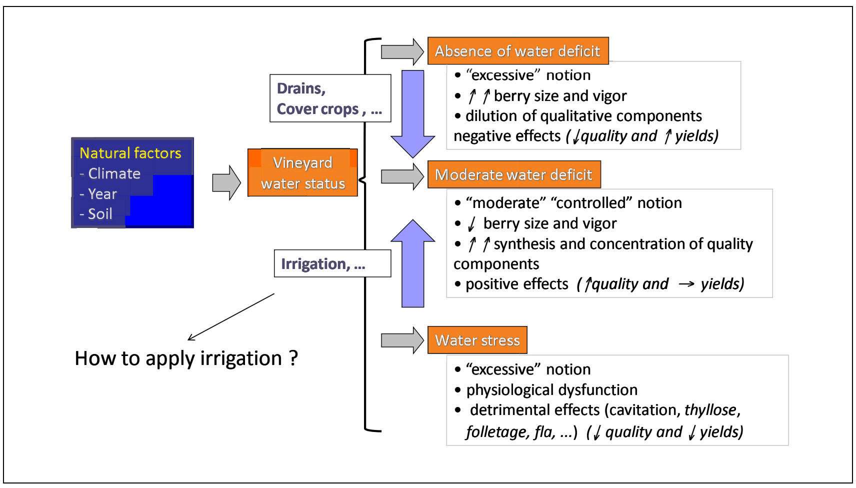

Figure 2. Different situations and possible consequences of vineyard water status according to the natural characteristics of the terroirs.

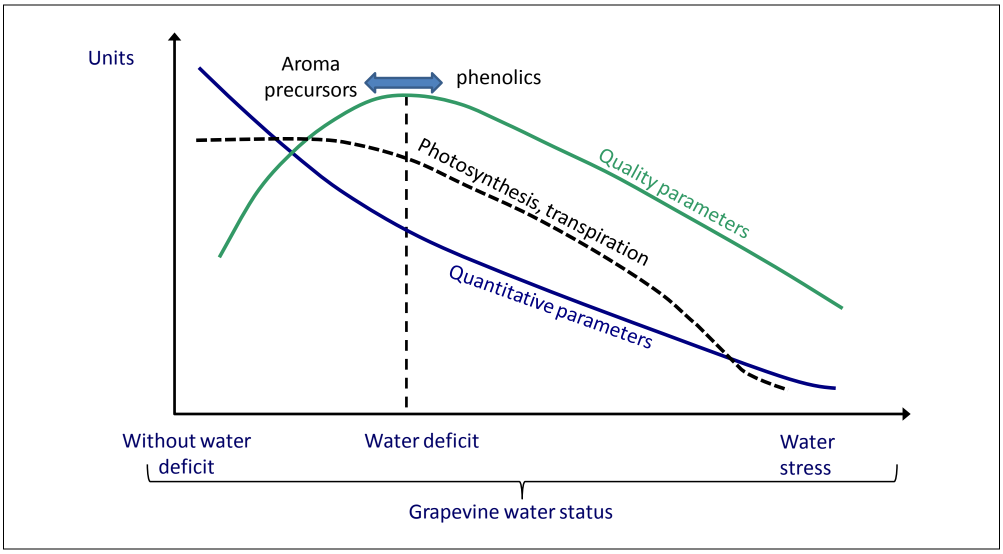

Figure 3. Influence of vineyard water status on qualitative, quantitative and physiological parameters.

occur because of small berries (Figure 3). However, above an optimal water deficit threshold, the grapes no more produce or accumulate the so-called « qualitative » components, while physiological activities (photosynthesis, stomatal conductance, transpiration, vegetative growth) are deeply reduced. This optimal water deficit threshold varies according to the desired quality parameter, like phenolic components in red wines or aroma precursors in white wines. More severe water deficit levels produce a strong reduction in qualitative, quantitative and physiological parameters. It may lead to a strong reduction of plant vigor that can cause survival problems for some varieties if this situation persists for several successive vintages.

These results justify the need to strengthen knowledge and establish optimal water status levels for each variety/training system/terroir situation for optimal quality/yield ratio. In parallel, investigation should continue to analyze the mechanisms of adaptation in different varieties. Important contributions are already available for the response curves of photosynthesis, transpiration and stomatal conductance to different water levels (Prieto *et al.*, 2012).

Irrigation methods

Traditionally, the methods used to irrigate grapevines were gravity and flood (Figure 4). This has limited the development of irrigation to areas where a systematic distribution of water and a proper site preparation was possible, and significant water resource was available. These methods resulted in large losses by leaching (over 50 %). The use of drip irrigation systems has been increasing in viticulture since the early 90s, mainly due to their ability to conserve water and accurate management. Today, drip irrigation is the most common irrigation method used in the world for viticulture.

Drip irrigation technology, when well managed, allows a better control of the vineyard water status ensuring an accurate, economical and automation water management. This method allows fertigation, i. e. the application of nutrients with irrigation. However, in some soils, monitoring salinity in the root bulb should be a permanent care. In some sandy soils, prolonged irrigation system failure can cause a very rapid drying of soil in contact with the root that can be catastrophic for the vine (Peacock *et al.*, 1977).

Irrigation strategies

Models for irrigation management based on the maintenance of an optimal level of plant water status along the growing cycle have been proposed (Ojeda, 2007, 2008). Different alternatives are available according to the vineyard objective, the soil fertility and the water deficit level (Figure 5).

For a vineyard dedicated to the production of grape juice with high yields, the irrigation strategy should avoid any water stress during the entire growing season (Figure 5A). The same strategy will be promoted for the production of basic wines or young vineyards.

When the objective is to produce an aromatic white wine or a fruity red wine, irrigation should be managed to ensure a slight and gradual water deficit towards the end of the veraison-maturity period (Figure 5B). This will maintain berry size and photosynthesis, favoring the accumulation of sugars and especially flavor precursors while controlling vegetative growth.

For more concentrated wines, a moderate and progressive water deficit during the maturation period will induce a reduction of berry size and total yield and promote the concentration and synthesis of phenolic compounds, including anthocyanins (Ojeda *et al.*, 2002) (Figure 5C).

For red wines, a more pronounced water deficit (Figure 5D) can ensure a greater control of berry size and a significant increase in the concentration of phenols (more color and structure) despite some reduction of aromatic intensity. This strategy is very suitable for red wines for aging. However, it is not recommended for white wines where the aromatic component is preferred (Peyrot des Gachons *et al.*, 2005).

The control of water availability in relation to the model can be very difficult in some extreme situations. In zones with deep soils, clayey texture, high clay and nitrogen content, and poor drainage, it must be necessary to control the excess of water through specific soil management techniques, the use of cover crops or canopy management. When the soil is sandy or sandy loam with good drainage, the risk of water stress is high; it is therefore necessary to regularly monitor the water status of the vineyard to prevent this risk.

Depending on the strategy, it is convenient to keep the vineyard at levels close to the optimum level of water status during the entire growing season to ensure maximum benefit and prevent problems caused by excess water or drought.

Based on these models, irrigation strategies began to be applied in different wine regions throughout the world, and several companies started to offer services and tools to support the producers in the implementation of these strategies.

Methods for decision support

Several direct and indirect techniques for the estimation of plant water status or available water resources have been proposed for grapevine. In general, they can be classified into two main groups:

- Methods based on direct measurements at plant level: stomatal conductance with potometers or gas exchange analyzers (Bravdo and Naor, 1996; Flexas *et al.*, 2002; Cifre *et al.*, 2005; Loveys *et al.*, 2005); leaf water potential with a pressure chamber (McCutchan and Shackel, 1992; Schultz, 1996; Choné *et al.*, 2001; Carbonneau *et al.*, 2004; Girona *et al.*, 2006; Sibille *et al.*, 2007); transpiration with

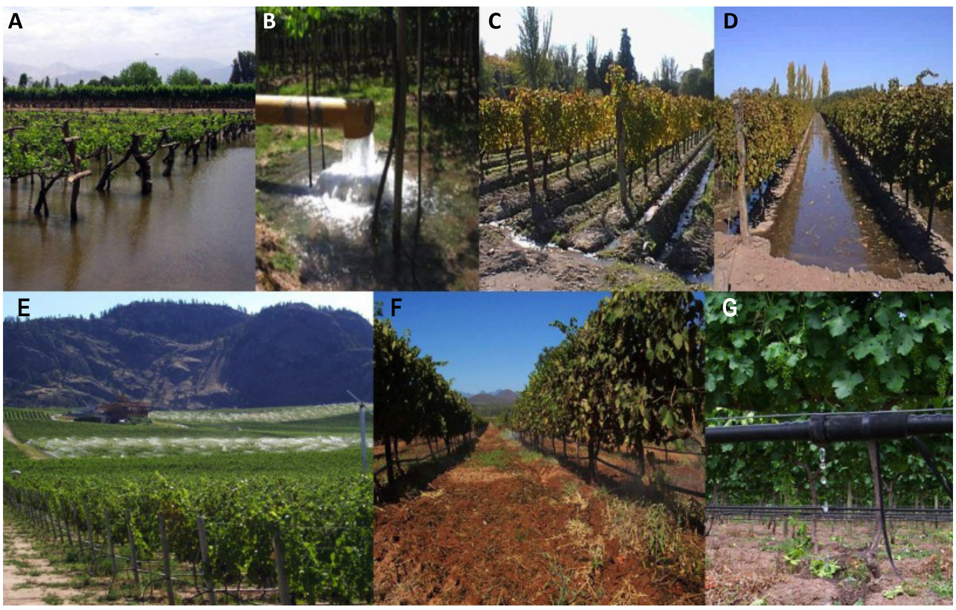

Figure 4. Different types of irrigation used for viticulture worldwide.
A: Submersion « pools » (Ica, Peru); B: « Californian » flood (Mendoza, Argentina); C: Gravity with « grooves »; D: Gravity with « melgas » (Mendoza, Argentina); E: Sprinkling (Osoyoos, Canada); F: Microsprinkling (Stellenbosch, South Africa); G: Drip (Mendoza, Argentina).

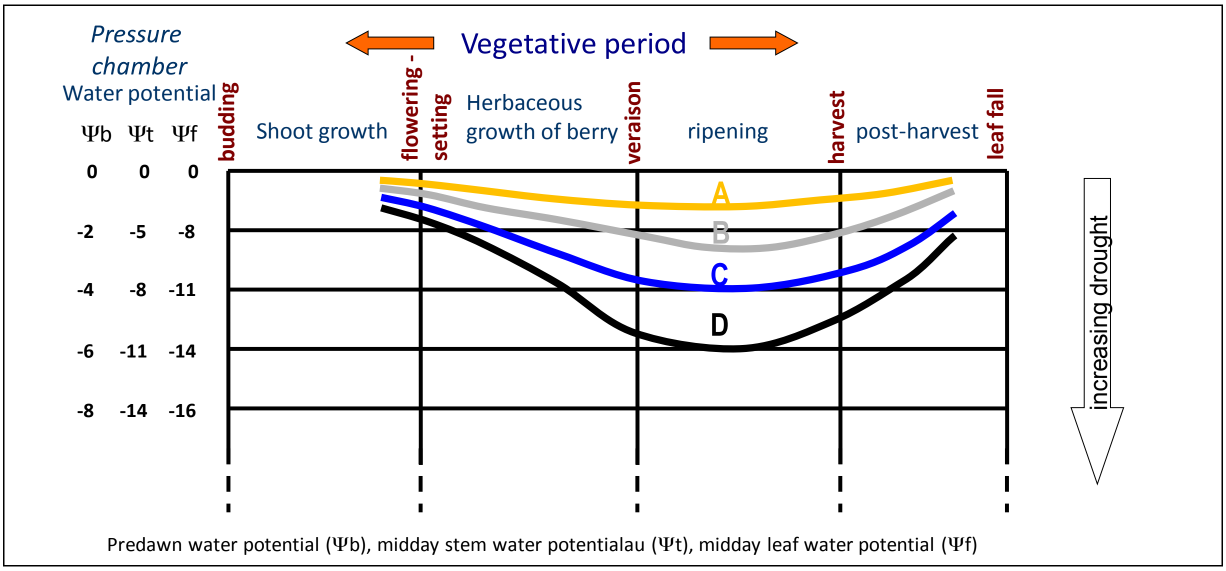

Figure 5. Possible different irrigation strategies to control the vineyard water status according to the growing cycle and the type of desired product. A: Concentrated musts, grape juice, table wines and young vineyards; B: White wines, light red and fruity wines; C: Young quality wines, well balanced and more fruit driven, limit values for white wines; and D: Quality wines, concentrated, balanced and suitable for aging.

sap flow sensors (Yunusa *et al.*, 2000; Fernandez *et al.*, 2001; Escalona *et al.*, 2002; Cifre *et al.*, 2005; Saurin *et al.*, 2011); plant water potential estimates with the use of hygrometers on the stem (Dixon and Tyree, 1984; Hessdörfer *et al.*, 2013); dendrometry to monitor trunk diameter fluctuations (Loveys *et al.*, 2000; Naor and Cohen, 2003; Cifre *et al.*, 2005); leaf and canopy temperature (Idso, 1982; Sinclair *et al.*, 1984; Jones, 1999; Jones *et al.*, 2002); or determination of the carbon isotopic ratio (13C/12C) on grapes (Van Leeuwen *et al.*, 2001; Gaudillère *et al.*, 2002).

- Methods not based on direct measurements at plant level: crop evapotranspiration estimates from climate data (Sammis *et al.*, 1988; Allen *et al.*, 1989; McCarthy, 1997; Pereira *et al.*, 1999); soil water availability (McCarthy, 1997; Lebon *et al.*, 2003; Pellegrino *et al.*, 2005, 2006; Loveys *et al.*, 2005); use of soil moisture sensors (tensiometers, electrical resistance, neutron probes, TDR and FDR probes, etc.) (Topp *et al.*, 1980; Ortega-Farías and Acevedo, 2004; Loveys *et al.*, 2005); or calculation of indices based on one or more methods (McCarthy, 1997; Colaizzi *et al.*, 2003; Ortega-Farías *et al.*, 2004).

Among all the potential tools and methods for the estimation of plant water status and water availability, it is advisable to favor those that are based on measurement of the physiological functioning of the plant because it integrates all the parameters responsible for the water status of the vineyard (ETP, rainfall, soil type, cropping practices, etc.).

The best method is still the determination of leaf water potential using a pressure chamber (Scholander *et al.*, 1965; Carbonneau, 1998; Choné *et al.*, 2001; Ojeda *et al.*, 2001; Williams and Araujo, 2002; Deloire *et al.*, 2005). It was gradually adopted by wine companies as a decision support tool for irrigation (Figure 6). Solid reference thresholds valid worldwide and for different agro-climatic conditions have been established, particularly for predawn leaf water potential.

Other techniques more relevant in a specific context, more economical or easier to implement can be useful and precise provided they are supported by the leaf water potential measurements.

Vineyard irrigation and consumer perception

Irrigation raises several concerns. From the producer side, the limitations linked to the Appellation system and the definition of terroir should be taken into account. From the consumers and civil society side, environmental and social issues such as water scarcity and saving and sharing resources should be considered seriously. Consequently, it is important to analyze the parameters that control the perception and acceptance of this practice.

Therefore, a study was performed to analyze the consumer's point of view about the impact of irrigation on the perceived wine quality. The methodology employed is based on previous works that show the relevance of the concept of « consumer's involvement » and of « involvement in environmental issues » as a criterion for consumer segmentation (Jourjon and Symoneaux, 2012, 2014; Wilson and Jourjon, 2012). This segmentation was used in 2015 to analyze the responses of 512 internet surveys. Results show that wine consumers seem to have divided opinions concerning irrigation: a majority seems to agree that an irrigation management strategy can be adapted to the quality concept of AOC wines. On the contrary, the rest of involved consumers are either against this idea or have no opinion. Finally, non-involved qualified consumers do not have any opinion concerning irrigation and mid-involved consumers are mainly favorable to an irrigation management strategy for AOC wines. Moreover, within involved consumers, age could be a parameter for acceptance of irrigation: senior consumers (>65 years old) are more likely to disagree with irrigation for AOC wines; young consumers (>35 years old) are more likely to agree with the possibility of irrigating. Less involved consumers have no clear opinion regarding the best way to adapt viticulture to climate change, they simply do not know. On the contrary, involved consumers indicate the use of irrigation for assuring the quality of AOC wines, next to selecting a variety more adapted to the new climate and to changing the localization of the plots within the region.

Conclusion

In the current context of climate change, the hypothesis of increasing drought conditions is widely supported at the scientific level. The vineyards of the Mediterranean area are the most affected, and the use of irrigation as a palliative method is constantly increasing. Irrigation, like any other practice, requires precise management to be effective. Current scientific knowledge allows laying the foundations for a sustainable management of grapevine irrigation, maximizing grape quality and saving water. Taking this knowledge into account, the regulation for the use of irrigation in vineyards should be modified and consumers should be better informed about this practice.

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Overcoming the final frontier of climate change in viticulture: exploring interactions between society and environment using Agent-Based Modelling and Companion Modelling approaches

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Abstract

Climate change is a complex process that requires societies to seek viable adaptation solutions. Agent-based modelling using co-constructed models can thus be seen as a means of understanding the manner in which societies in wine-growing areas take into account the different variables that influence their systems. Here we offer a reflection on three years of companion modelling carried out in the AOC Banyuls-Collioure (Fr) and Val di Cembra (It). This work has led us to co-construct six agent-based models and to produce a future-oriented summary, enabling us to identify the macro-variables that influence these environments.

Keywords: agent-based model (ABM), companion modelling, systemic approach, stakeholders, landscape

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Introduction

Climate change is a complex process that highlights gaps in our ability to understand the underlying drivers. Most of the controversial gaps have an anthropogenic origin (Guillemot, 2014) and raise questions about societies' ability to adapt to climate change. These questions and solutions for adapting to climate change seem too complex, and the uncertainties too large, to be left to a formal, disciplinary scientific approach. Funtowicz and Ravetz (1993) suggest resorting to "post-normal" science. This involves tackling complex problems in an inter-disciplinary manner, including bringing in various stakeholders, in order to provide and integrate solutions into societies.

In this paper, after reviewing current work in agent-based modelling used in climate change context, we propose the use of multi-agent systems (MAS), adopting a companion modelling approach. The co-construction method was used on six models, in collaboration with stakeholders, in two wine-growing areas: the AOC Banyuls-Collioure (Fr) and Val di Cembra (It).

Each co-constructed/companion model leads to a partial understanding of the system. However, when these models are considered as a system, they allow us to outline stakeholders' perception abilities of these environments.

A short introduction to agent-based modelling

1. What is modelling?

The concept of modelling is part of the scientific approach. A model is a simplified representation that allows us to think the world based on hypotheses. Modelling is therefore an intellectual construction that i) involves interactions between a range of ideas and concepts, and ii) allows to put together reasoned arguments suitable for sharing (Le Page *et al.*, 2010).

Multi-agent modelling emerged in the 1980s from the crossover between computing (object-oriented programming, distributed systems, etc.) and distributed artificial intelligence (artificial life, robotics, cognitive sciences). Ferber (1995) stresses that the development of distributed artificial intelligence requires several conditions, including i) the need for a system to "*adapt itself to the modifications of its structure or its environment*" and ii) a "*complex problem that calls for a local perspective.*" An agent is defined as "*a physical or virtual entity that: a. can act in an environment, b. can communicate directly with other agents, c. is driven by a set of trends (in the form of individual objectives or functions that must be optimised), d. has its own resources, e. can perceive its environment, f. has only a partial vision of this environment, g. possesses skills and offers services, h. might be able to reproduce itself, and i. adopts behaviour in order to meet its objectives, taking into account the available resources and the perceived images and received information.*" (Ferber, 1995).

We are interested here in the use of modelling and multi-agent simulation in social sciences, in the same way they are used in experimental sciences, as a tool allowing us to access *in silico* (Knibbe, 2013) socio-spatial configurations that are difficult to tackle by conventional methods. By applying these models, social scientists can access the field of experimental scientists (Peschard, 2011) in the same way that biologists use the "Petri dish".

2. From system to model: theorising the world?

Systemic modelling has been developed in the middle of the 20th century, in a cross-disciplinary approach that broke away from reductionist modelling. This approach allows us to think complex objects as a whole. The systemic approach can be linked to various scientific disciplines having an ambition to theorise. For Pumain (2003, p. 27): "*To theorise is, first of all, to try to escape from the paradox of "pure science" and, above all, to look beyond the irreducible oneness of things, to try to construct a nomothetic view of the discipline.*"

Moving towards a systemic approach is therefore not neutral and involves going beyond the "tangible/real". This scientific position offers the possibility to grow in abstraction and think easily transferable theoretical generalisations.

In France, when looking at viticulture, we can single out the attempt of systemisation proposed by Auriac (1979). This work, using General System Theory (GST), offers a new approach to viticulture geography by theorising the "vineyard-system" as a dynamic object.

3. Roles and status of the model

This need to step back from "concrete" forms of the world became apparent during the 20th century and was a definitive turning point for scientific models. It raises questions about the emerging need for theorisation in all the scientific disciplines.

Researchers (as observers) must change their point of view and concentrate on the phenomena of form generators. Thom (2009) questions this observer role:

"*Can someone, in a landscape of phenomena, recognise an object if there is prior concept of it? It's as simple as that. If you don't have a concept of an object, you cannot recognise it. [...] The possibility of recognition of an entity in an empiric landscape is always subject to conceptualisation.*"

This link between conceptualisation/formalisation and the recognition of a pattern in the results requires proceeding from an iterative basis by confronting hypotheses with experimentation and then by rejecting or confirming these hypotheses.

4. Empiricism and ABM/MAS: an empty space for post-normal science

One of the challenges in social sciences has always been to move from the description of reality to the abstraction that leads to theorisation. At the same time, more and more interdisciplinary studies try to understand interactions and associated organisations rather than predict the state of a future system (Etienne, 2013). When the questions of research collide with great uncertainties and face major social issues, their resolution goes beyond the factual scope of science, leading to the paradigm of "post-normal" sciences (Funtowicz and Ravetz, 1993). The "post-normal" approach does not banish the uncertainties but seeks to overcome them by including the stakeholders (Funtowicz and Ravetz 1993, p. 740). The quality of the solution to the problem depends not only on scientific abstraction but also on the decision-making process (Etienne, 2013). The role of the scientist is thus redefined as a guide in this process. It reintroduces the legitimacy of an empirical approach.

However, empirical agent-based modelling approaches must translate the real world into a robust model. For Smajgl and Barreteau (2013), this translation is equivalent to bringing together a range of parameters from heterogeneous sources, with a range of valid results from observation and measurements. Moreover, agent-based modelling mobilises more complex information than the links between model inputs and outputs: "*It also provides information on the structure of the population of the target system so that up-scaling can be performed to generate a suitable artificial population. [...] Parameterisation is not only a matter of giving quantitative value to parameters, but also a matter of being able to run the model with a set of values. Sets of categories are particularly useful for qualitative or fuzzy approaches.*" (Smajgl and Barreteau, 2013, p. 3).

Climate change, land use adaptation and ABM

1. Climate change and adaptation

For over twenty years, IPCC has been working on long-term evolution of climate change, making populations aware of climate-related impacts that may arise. Climate change has become a key issue for viticulture (Nemani *et al.*, 2001; Jones *et al.*, 2005; White *et al.*, 2006; Schultz, 2010). At the same time, controversies have emerged regarding the future of viticulture (Hannah *et al.*, 2013 vs. Van Leeuwen *et al.*, 2013). Even though climate change itself is no longer disputed, the ability of wine-growers to take advantage of their environmental and cultural practices is now in question, as raised in the research program LACCAVE[1] (2012-2015) (Barbeau *et al.*, 2014; Ollat and Touzard, 2014; Viguié *et al.*, 2014; Neethling *et al.*, 2016).

2. Climate change and ABM

Investigating climate change issues through MAS leads to difficulties: i) the processes that influence climate change are not precisely understood and ii) no social theories are universally suitable in this context (Moss *et al.*, 2001). In general, the studies we identified on wine growing tend to address the society-environment link in economic terms.

The objective of these models is to offer to decision makers a theoretical framework that helps them to think about the effects of climate change. The "social" agents of the model are trying to maximise their revenues in a system facing several constraints. By trying to sum up the knowledge of the subject, the modellers have a dilemma about the degree of formality and the degree of abstraction of the models (Moss *et al.*, 2001; Banos and Sanders, 2013). Using the classification method suggested by Banos and Sanders (2013), we studied eight articles that tackle climate change in viticulture from a MAS perspective.

By placing each of these studies in a "horseshoe" grid (figure 1), we notice that none of them are in the A or B part of figure 1. This absence reveals science's lack of objectivity regarding climate change and the difficulties to raise the level of abstraction. Also, all these studies are based on particular viticulture areas and use formalism tending towards KIDS[2] (Edmonds and Moss, 2005).

[1]LACCAVE: Long-term impacts and Adaptations to Climate Change in Viticulture and Enology.

[2]KIDS, short for *Keep It Descriptive and Stupid*, is a modelling approach that seeks to describe interactions between agents as precisely as possible.

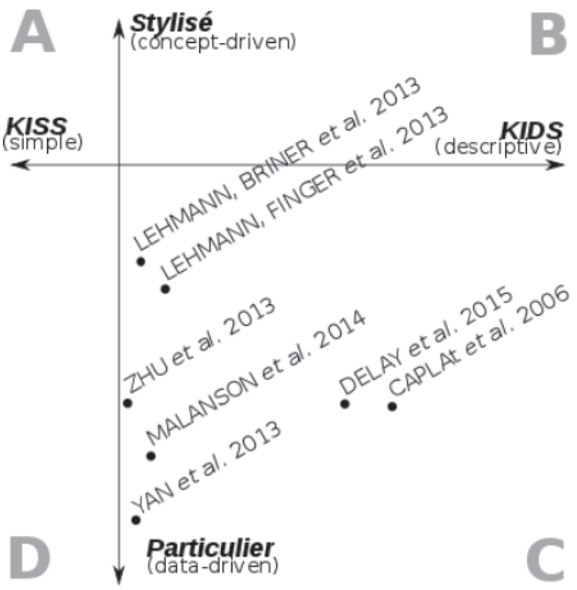

Figure 1. Placing the models in a "horseshoe" grid, as suggested by Banos and Sanders (2013).

This over-representation probably results from the need to base the models on a "target area", where the efficiency and robustness of the model are tested. This local dependency is generally due to the access to climate data and/or to the methods of gathering social information, focusing on understanding the dynamics of a focal point. After that it is hard to go from a quite descriptive model to a more abstract and concept-driven model.

Examples of the use of ABM in understanding complex local socio-systems subject to climate change constraints

The interdisciplinary nature of multi-agent modelling applied to viticulture under climate change led us to adopt a "post-normal" stance, involving all stakeholders in the modelling process (Funtowicz and Ravetz, 1993). Nevertheless, the range of problems to be addressed is so wide that implementing a co-construction with all of these actors and their points of view appeared impossible. To include multiple viewpoints and designs into an object covering many forms of reality (Watzlawick, 1976), we suggested an approach that combines several models controlled by the analysis of the constraints and uncertainties of their uses (Delay, 2015).

Thus, based on the work of Neumann (2015), we first constructed an ontology on the field of viticulture under climate change (Delay, 2015). Then we co-constructed, along with the stakeholders, six models, each responding to questions arising locally and corresponding to a limited part of the ontological domain, somewhat like a fragmented vision of the world. We will present them in pairs, and then we will show the relationship between them.

1. Large spatial scale: the pathway to abstraction

The first models are "Dion still alive" and VICTOR: two multi-agent models that simulate the viticulture area on a small scale with agents aggregated in the towns, villages and market places. These two models replace the steep slope viticulture in the "viticulture-system" by focusing our attention on the effects that orography has on the structuring and the dynamics of wine-growing areas. These two abstract models are based on theoretical data and knowledge. Their interest (for scientists and technicians) relies on the validation of relationships and processes necessary to generate the spatial dynamics observed in real life. Observable emergence enables us to hypothesise and explore the implications that theoretical parameter might have on space and time.

The "Dion still alive model" (Delay and Chevalier, 2015) proposes to revisit the hypotheses put forward by Dion (1952) in his article "Querelle des anciens et des modernes sur les facteurs de la qualité du vin" ("Quarrel between traditionalists and modernists about wine quality factors"). This work, apart from the reinterpretation of Dion with regard to simulation, also prompts us to reflect about formalism in the long-term evolution of quality. Here, the slope is a quality criteria much sought by the agents, influencing the global spatial dynamics.

The VICTOR model (Delay, Leturcq, and Rodier in press) explores the agricultural dynamics that arises in a wine-growing area when competition between two crops, vines and cereals, is introduced. This model is therefore used to simulate the effect of different types of market on local communities. Here we explored the effect of economic stimulation on the wine-growing area when it is in competition with subsistence farming. In this case, sloping land is considered as a poor environment, unfavourable for cereal production. It therefore represents a refuge space for viticulture even when economic conditions favour cereals.

2. Meso-scale: towards taking into account viticulture dynamics

Next we explore "individual-centred" models at greater spatial scales using the LAME (Delay *et al.* 2012) and CiVIsMe (Delay, Chevalier *et al.* 2015) models. These models attempt to formalise individuals' behaviours in a simplistic way, which, in a "principle of plausibility" (Varenne 2011), allow us to consider the spatial dynamics of the vineyard. The iterative construction of these models with local actors[3] ensures this "plausibility of principle" with the reality of the wine-growing area.

The LAME model explores the importance of environmental factors, such as slope and accessibility, taking into account how the winegrowers choose the place of plantation, reusing or abandoning their plots. This work is first carried out in an artificial environment, and then with real data.

The CiVIsMe model studies the ever-present cooperative effect found in many vineyards located in difficult geographical conditions. We use it to evaluate the implications of the grape payment rules in the cooperatives. This model also allows to identify the influence of land structure and thus to explain any local differences that might arise in cooperative behaviours.

3. Finer spatial scales and local dynamics: abstraction assists in considering local dynamics

In this last "downscaling" stage, we focused on very specific processes. Our objective was to respond to the particular needs of the stakeholders involved in our study. These winegrowers and technicians, who participated in the other modelling approaches by validating performance and discussing hypotheses and results, were especially interested in local models. We therefore submitted the next two models, acidityGIS (Delay, Piou, and Quenol, 2015) and CeLL (Delay and Caffarra, 2015), in response to their requests. These models integrate economic data, along with spatial temperature data, in order to assess the impact of spatial heterogeneity on the models' performance.

Considering the impacts of climate change at the Mediterranean basin scale like Hannah *et al.* (2013) does not consider all adaptation available at the small-scale level (van Leeuwen *et al.*, 2013). The wine-growing area of Côte Vermeille is at greater risk from climate change than other regions. The acidityGIS model, used in a cooperative context, explores the possibilities offered by orography to maintain grape ripening according to the specifications of the AOC[4] system.

The CeLL model aims to offer winegrowers food for thought about their pest (insect)-control methods. CeLL models the behaviour of a vine parasite known as Eudémis or European Grapevine moth (*Lobesia botrana*). This Lepidoptera, which lays its eggs under the skin of the grape, is particularly temperature-sensitive. By means of an "individual-centred" model, we simulate the behaviour of butterfly populations on a small scale in order to optimise pest-control strategies by the use of pheromone traps. The development of the CeLL model allows us to test *in silico* a certain number of variables and to show the potential results of different integrated pest management approaches.

The integration of MAS in a local prospective approach

Considering an area and climate change via several models has two advantages: i) it produces direct results on which the stakeholders can act and ii) it offers the researchers a set of models addressing the subject from different angles, each corresponding to the point of view of a particular group of actors. In the following section, we present the second advantage of this multi-model approach.[5]

1. Looking ahead using a system of variables built on models

For the researcher who wants to explore the future by using a set of models, the challenge is to build a meta-model that helps to "think ahead".[6]

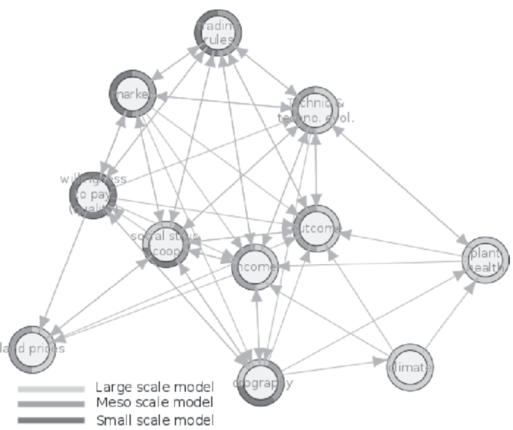

Figure 2. Diagram showing the interaction between structural macro-variables, in which we can observe the different spatial scales that apply to each variable.

[3]The actors in this case are technicians from local organisations, such as the chamber of agriculture, the winegrowers' syndicates, agricultural cooperatives, etc.

[4]Optimising the double ripening of berries: polyphenolic maturity and technological maturity.

[5]The contribution of the method, producing results that can be used by stakeholders, was described by Delay, Piou and Quenol (2015) and Delay and Caffarra (2015).

[6]We were inspired here by the work of Hannin *et al.* (2010, p. 227), who identified 50 traits specific to viticulture.

The MicMac method[7] put forward by Godet (1985) suggests the use of structural variables coupled with an approach based on graph theory in order to analyse interactions between different variables. We identified 11 macro-variables resulting in the clustering of several modelled processes.

The second stage of the method consists in studying the types of relationship between the variables, constructing a network of dependencies based on graph theory. Figure 2 shows the interactions between the macro-variables from the models co-constructed with the stakeholders. This graph therefore represents the systemic vision that the stakeholders developed, in other words, a synthesis of the abstraction that the stakeholders made via the modelling work we carried out with them.

The stakeholders from the Banyuls region verified this system of variables during a round table workshop.

This meeting brought to light a perception shared by the winegrowing community. We noticed the actors' underestimation of the importance of the community level and the predominance of the global context, to which they respond mainly at an individual level. This shows their difficulties in participating in the cooperative organisations, which represent the broad majority of actors in this area, as they refuse to question[8] their collective rules and attribute their difficulties to external forces.

Focusing on climate and climate change, we see that these issues are indeed present in the minds of the stakeholders but that the solutions for adaptation are found on a local scale. Individually and collectively, they feel that it is impossible to influence global dynamics. Nevertheless, local adaptation is possible (van Leeuwen *et al.*, 2013; Viguié *et al.*, 2014) by redistributing the space constraints and using orography to respond to these new constraints.

Conclusion

Agent-based models and complexity science are tools to help us consider the world in an integrated approach. These tools can be used as such to provide answers to social questions. The combined use of several models as prospective tools can offer a systemic approach to the projection issues met by the stakeholders.

The construction, or co-construction with the stakeholders, of models allows access to what Weber (1922) identifies as "causal adequacy". This corresponds to identifying consistent interactions from the point of view of the actors (empirical).

At the same time, "meaningful adequacy" (Weber, 1922), that is to say consistent with reality, is identified in the general discussion during the validation exercise. The "distance" between these two types of adequacy shown in the macro-variable systems helps us to understand how the stakeholders think about their area and their interactions. Thus, while the levers for adjustments and local dynamics can be partially put into motion by the stakeholders on an individual basis, a great number of variables, on a more global level (market, or trading rules, etc.), remains beyond their grasp.

The findings of these modelling-based studies demonstrate the need for quite specific local adaptations. A question remains regarding the flexibility of our system of variables. It will be interesting in the future to continue to explore configurations where orography is less important in order to i) evaluate the (longer term) durability of the variables in the systems and ii) identify other levers of local adaptation that could be transferable into different contexts.

[7] "Matrice d'Impacts Croisés - Multiplication appliquée à un Classement".

[8] At the same time, the actors regularly question the workings of the models. Two of the six models developed concern in particular the cooperative objective, while another explores the "cooperative factor" in insect pest control.

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Models	Question	Public	Space Scale	Time Scale	Entity
Dion still alive	What is the influence of an external market on the spatial structuration of vineyard areas?	Researchers	Regional abstract space	Year	Vine plot, local wine market, external wine market
ViCTOr	What happens spatially when vine plot is in competition with grain?	Researchers	Local community abstract space	Year	Vine plot, grain plot, village
LAME	How does steep slope influence spatial choices and spatial distribution of vine plot?	Researchers and technicians	Abstract steep slope space	Year	Vine plot, winegrowers
CiVIsMe	How do cooperation and cooperative influence the socio-spatial dynamics of steep slope vineyard plots?	Technicians	Abstract steep slope space	Year	Vine plot, winegrowers and cooperatives
AcidityGIS	How can cooperatives manage the vineyard in a climate change context?	Technicians and winegrowers	Banyuls-sur-Mer (Fr)	Year	Vine plot, winegrowers and cooperatives
CeLL	How can integrated pest management be optimised by better spatial organisation of pheromone diffuser in a small watershed?	Technicians and winegrowers	Banyuls-sur-Mer (Fr) and Cembra (It)	Day	*L. botrana*, vine plots and pheromone diffuser

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Spatially-explicit modelling of past long-term evolution of a vineyard landscape

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Abstract

Climate change and evolution of land uses are interrelated, and it is of primary importance to analyze and simulate factors of land use evolution to project these trends in a context of global warming. Among the various landscapes susceptible to climate warming, vineyards are influenced by climate, agronomic and sociological factors. Since the post-war years, the wine-growing crisis, the changes in consumer habits and vineyard mechanization have deeply affected landscape architecture and composition of vineyards in South of France. The analysis of factors determining landscape evolution through retro-observation helps us simulating the future landscape for planning purposes. Here, we analyzed the introduction of mechanization in a 1 km^2 vineyard though the digitalization of aerial and satellite images from 1954 to 2012. Mechanization is detected in these images by the change in vineyard planting from staggered to straight rows. Other land uses, such as semi-natural habitats, forests, orchards, other cultures and urban zones, are classified in the images. A probabilistic model based on a Markovian process and calibrated using a random forest algorithm is developed on the basis of the data generated. The model simulates landscape evolution at decade and field scale. As a perspective, the model calibrated on this example could be used to test the introduction of new innovations to adapt the vineyard to climate change, such as the introduction of irrigation or drought-resistant varieties.

Keywords: spatially-explicit modelling, teledetection, land use, innovation

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Introduction

Climate change and dynamics of land uses are interrelated. On the one hand, the evolution of land use during the industrial era, due to replacement of forests by agricultural cropping and grazing lands, leads to changes in the physical properties of land surfaces and, consequently, to a temperature increase (Pielke *et al.*, 2002). On the other hand, warming is expected to lead to a northward expansion of suitable cropping area (Olesen and Bindi, 2002) and a shift of forest distributions in response to climate variation (Allen and Breshears, 1998, Bonan, 2008). Climate change increases the risk of insect outbreaks that cause crop damages (Bebber *et al.*, 2013) and tree mortality (Harvell *et al.,* 2002, Kurz *et al.,* 2008), leading to a substantial decrease of vulnerable land uses. Climate change also increases the risk of extreme weather events such as higher annual precipitation and more frequent high intensity rainfall events, leading to a severe impact on soil erosion (Nearing *et al.,* 2004).

Agriculture must adapt to climate change given the strong trends in climate change that are already evident (Howden *et al.,* 2007). The driving forces of agriculture adaptation must be understood to model present land system for predicting land cover changes in response to socio-economical and climatic trends in the following years. However, the projection of future landscape changes requires the integration of past landscape trends and current land change processes (Houet *et al.,* 2010). Among the various landscape types, Mediterranean landscapes are a unique combination of climate, relief, soil and human use over thousands of years (Naveh and Kutiel, 1990).

Typical landscapes of the Languedoc region are mostly covered by vines and cereals (Biarnes *et al.,* 2009). Vineyards represent a strong cultural legacy and support a crucial socio-economic sector (Salome *et al.,* 2014), despite that the sustainability of these landscapes has been threatened by several crises. In the 1860s the phylloxera aphid caused a total collapse of vineyard production in Europe until the successful grafting on American vines. In 1907, an overproduction of Languedoc vines caused an abrupt decrease in the number of vine growers (Auriac, 1983). The introduction of the Common Market in 1970, which allowed the Italians and Spanish to invest the French domestic market, caused a decrease in table grape production (Galet, 2008), combined with a decrease in pesticides used in agriculture. In 1990, the arrival of « New World » vines from the United States, Australia and Chili has influenced vine production. These crises had profound impacts on vine production in terms of both quantity and quality. There has been a great reduction in the total area of French vineyards and a replantation of grapevines due to the changes in wine consumption from quantity to quality (Galet, 2008). All these events have impacted the spatial arrangement of vineyards. The comprehension of spatial determinants of landscape evolution is of primary importance to help modelling the future of these areas under socio-economic and climate changes.

The analysis of landscape evolution depends on the amount of data available spatially and temporally. In France, the Institut Géographique National (IGN) provides both aerial and satellite images at various resolutions. We selected as a case study the impact of mechanization in vineyards onrow spacing and arrangement. This modification of vineyard spatial arrangement, from staggered rows to straight rows, corresponding to goblet and aligned vineyards, respectively, could be detected from aerial photographs. Thanks to a large database of historical photographs from aerial campaigns realized in the Languedoc region from 1954 to 2003, and satellite images taken from 2005 to 2012, we constituted a spatially-explicit, high resolution diachronic dataset of land use and land cover of a 1 km^2 vineyard. We used this dataset to apply a new methodology using learning algorithms (random forest and neural networks) to detect and simulate temporal breaks in Land Use Cover Change (LUCC).

Material and methods

The study area corresponds to a watershed that covers approximately 1 km^2 near the town of “Roujan”, 60 km west of the city of Montpellier (France). The area has gentle topography and is mostly covered by vines. The climate is sub-Mediterranean sub-humid with a long dry season, an average annual temperature of 14 °C and an annual rainfall varying between 400 and 1400 mm. The data gathered 15 aerial images from 1954 to 2003 coded in gray levels and 5 satellite images from 2005 to 2012 coded in three bands. Pixel resolution ranged from 0.2 to 1 m with an average of 0.5 m. The geomorphology of the zone was determined using a digital elevation model (DEM) at 0.5-m resolution. Aerial images previously georeferenced and orthorectified and satellite images were digitized on the basis of plot limits and road network and classified using 11 classes.

The description of “roads”, “urban area”, “woodland”, “fallow land” and “orchards” classes was performed considering the third level of Corine Land Cover nomenclature and expanding to a fourth level for the different vineyards: goblet and aligned. When distinction between two classes was difficult, a third class was considered, such as "semi-natural land" between "fallow land"/"woodland", and "undetermined vineyard" between "goblet/aligned vineyards". The "other crops" class exhibited a homogeneous texture featuring tilled ground or planted ground with annual crops.

Dynamics of the land use during the 58-year period was analyzed using basic statistics: total area per land use and transition probabilities for each land use from a given date to the following one. Vector data were rasterized on a 0.5-m-resolution grid chosen according to the minimal size of 99% of the plots, i.e. 0.27 m^2. The rasterization procedure was necessary to deal with time-varying plots during the period. The performed analysis helps detect break dates and cut the period in homogeneous parts.

Identification of the determinants of land use dynamics was performed using multinomial classification algorithm considering the land use classes per plot as an explained variable and (i) static variables: the DEM, variables derived from the DEM (slope, aspect, shadow), (ii) temporal variables: the previous and dominant land use of the previous plot considering two superposed rasters from date n and date n-1, and (iii) spatial variables: considering a set of plots contiguous to the previous plot, the spatial variable corresponds to their proportion sharing the land use of the central plot.

Simulation of land use dynamics and validation procedure were performed on the predictive abilities of two random forest classification models calibrated on the variables described before, the first one calibrated on the beginning of the period, and the second one on two calibration periods: at the beginning and during the break date (1981-1985) (Figure 1b). The comparison between trends in total area per land use was performed using RMSE, and

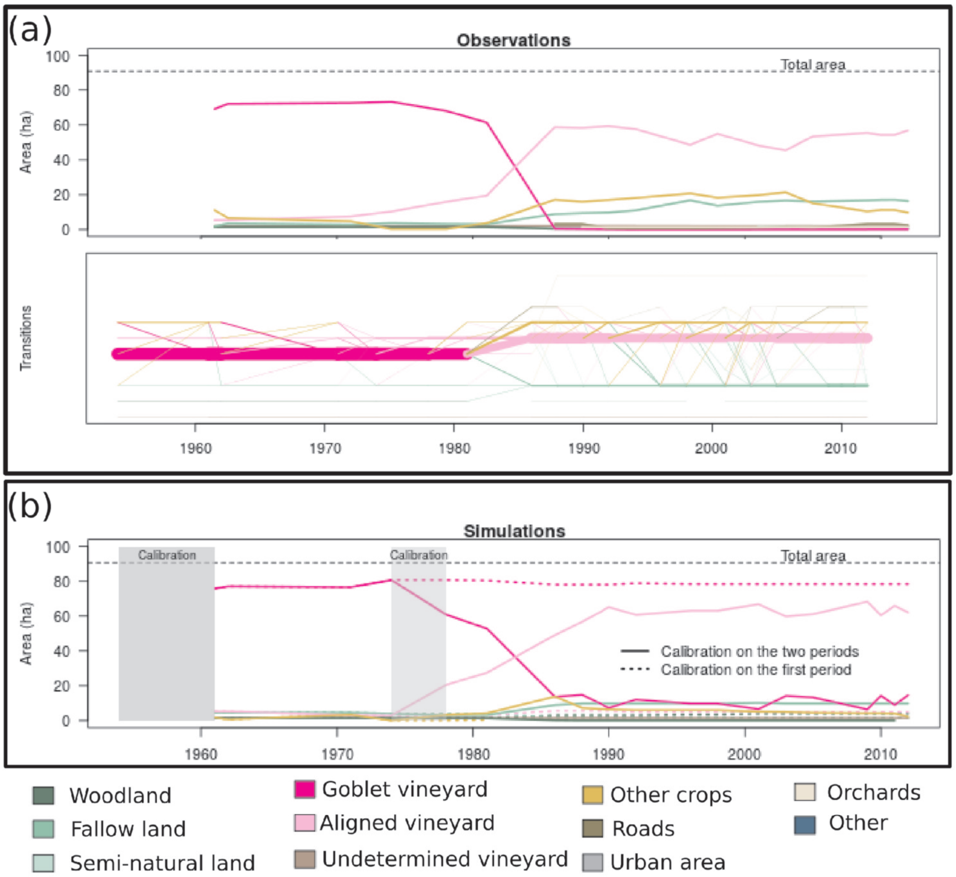

Figure 1. Dynamics of land use over the study area. (a) Evolution of observed land uses over time (indicated by lines), then transition dynamics between land uses. Transition diagram depicts flow of land classes from a given year to the following one; line thickness is proportional to the mag-nitude of the flow, and color corresponds to the land class of destination. (b) Evolution of simulated land uses as calibrated on two short periods. The calibration periods are defined by grey rectangles.

Table 1 - RMSE on observed versus simulated allocation areas for land classes, cumulated over the whole period.

Land use class	Calibration on one period	Calibration on two periods
Woodland	2.7	0.3
Fallow land	10.8	4.5
Goblet vineyard	48.1	34.0
Aligned vineyard	41.0	9.1
Other crops	12.8	9.2

the simulated spatial distributions of the plots were compared to the observed ones.

Results and discussion

We distinguish five main land use classes according to their total areas: goblet vineyard, aligned vineyard, fallow land, woodland and other crops; the six other classes accounted for less than 1% of the total area. The dynamics of land use presented two contrasted periods: 1954-1981 and 1986-2012 (Figure 1a). On the total number of transition probabilities from a given land use to another (11^2=121) per date, only 6 probabilities had a maximal value above 10%, with a large majority of probabilities representing an absence of land use change. Two probabilities represented the abrupt decrease of goblet vineyard areas in favor to both aligned vineyards and other crops (Figure 1a).

The multinomial classification algorithm helped disentangle the static, temporal and spatial variables explaining the land use classes on the basis of the relative importance and sign of the multinomial model coefficients. We selected only the significant variables using Wald tests, i.e. testing the null hypothesis of the corresponding coefficient being 0 (Williams, 1991). Considering static variables, the slope is positively related to the woodland and fallow land zones for each date. For temporal variables, coefficients related to persistence of land classes, i.e. coefficient describing the probability of a given land class to remain the same between two consecutive years, were higher during the 1954-1981 period than the 1986-2012 period.

There was no clear trend regarding coefficients related to spatial variables.

he random forest classification algorithm was chosen for prediction purposes instead of the multinomial model because of its best predictions (data not shown). The model calibrated on two short periods (Figure 1b) was able to represent distribution dynamics of land class areas with a higher accuracy than when calibrated on the first period (Table 1). It underestimated the transition from goblet vineyard to other crops and fallow land (Figure 1b). The spatial distribution of land use was also better predicted with a random forest model (correlations ranging from 0.6 to 0.9) than with a random arrangement model. Figure 2 shows the maps of the landscape for three years corresponding to the situation before the abrupt decrease of vineyard area, just after and at the end of the period.

Discussion

The random forest model gave better results than the multimodal one because of over-fitting. The best way to avoid over-fitting should be to realize cross-validation on a dataset at a larger extent than the study. Other statistical tools, such as partial least square regression or multimodal inference, were not considered in our study, as they were not appropriate in case of non-normality of the explained variables.

The sudden conversion occurring during the 80s (transition from goblet vines towards trellised vines) coincides with the arrival of mechanization in viticulture in the Hérault region. Agricultural machines need space between vines and it is easier to treat them if they are aligned. Furthermore, the decrease in vineyard area confirms the overall trend in the region following the French wine crisis that occurred in the 80's (Touzard and Laporte, 1998).

The retrospective analysis needed spatial data at fine temporal and spatial resolution levels to be achieved. The post-processing is time consuming and necessitates several corrections from distortion effects or planimetric errors but this work could be improved through constant amelioration of photogrammetric softwares. The study could be conducted in several other vineyard regions, assuming that aerial missions have been conducted in the area and recorded by IGN (http://www.geoportail. gouv.fr/accueil). For example, 94 missions from 1930 to 2016 have been realized near Bordeaux (France) and 157 missions

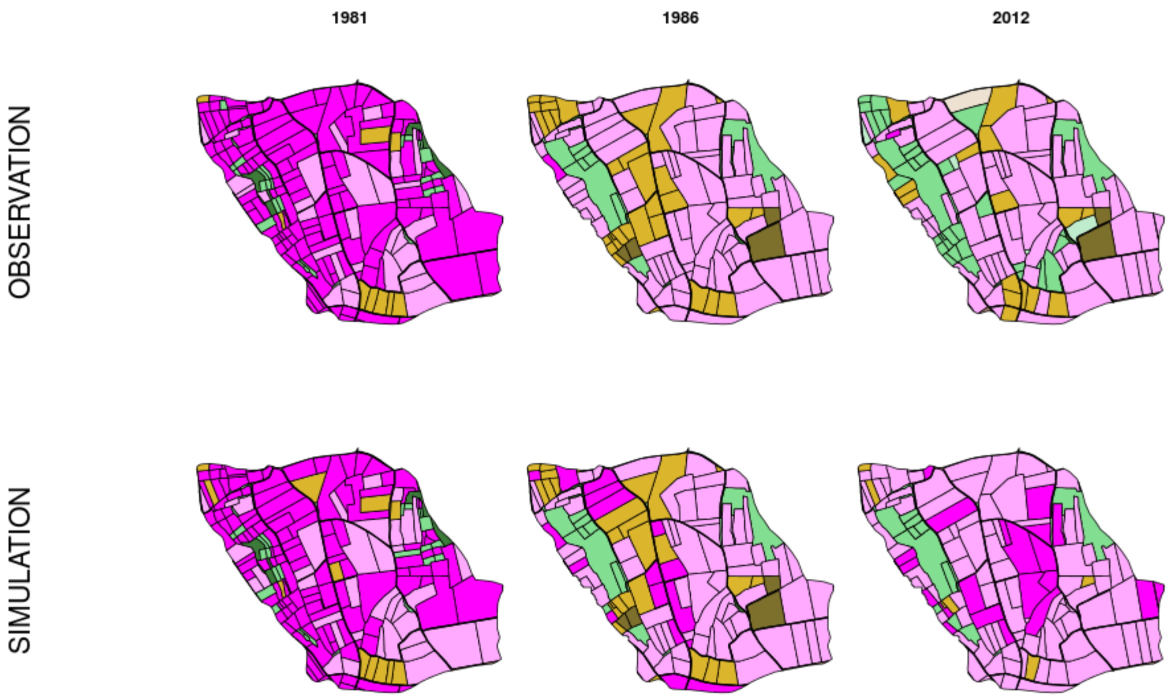

Figure 2. Illustration of simulated versus observed land uses over the Roujan watershed (see Figure 1 for color legend).

from 1919 to 2016 near Châteauneuf-du-Pape, which could be processed according to the framework described in this paper.

Moving from retrospective analyses to prospective ones necessitates including plausible assumptions of scenarios due to climate change (Houet *et al.*, 2010). In a scenario minimizing the impact of climate change, the introduction of new varieties of vineyards resistant to drought or irrigation spread over the watershed could be innovative solutions to fight against severe drought for example. Adapting these innovative strategies in the model necessitates a calibration procedure on existing cases and an extrapolation on our study area.

Conclusions

The use of learning algorithms for calibration of spatially-explicit model of land use is now possible considering the improvement of computer calculations on large database (Chang *et al.*, 2010). The combination of multinomial model for explanation of landscape patterns and random forest model for prediction will help researchers disentangle the complex links between static component (pedology, geomorphology, etc.), temporal component (previous land use) and spatial component (neighboring plots) shaping the landscape.

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How to adapt winemaking practices to modified grape composition under climate change conditions

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Abstract

Aim: In the context of climate change, adaptation of enological practices and implementation of novel techniques are major challenges for winemakers. The potential interventions are linked in particular with the alcohol content and the global acidity of wine. Here, we review current microbiological and technological strategies to overcome such issues.

Methods and results: Reducing ethanol concentration poses a number of technical and scientific challenges, in particular looking for specific yeast strains with lower alcohol yield. Several non-genetically modified organism (GMO) strains – *S. cerevisiae* or interspecific hybrids of the *Saccharomyces* genus – have yet been developed using different strategies, and some of them allow decreasing the final ethanol concentration by up to 1%. Several membrane-based technologies have also been developed not only to reduce the ethanol content of wines but also to increase the acidity and more generally to control the wine pH.

New strategies are also proposed to improve the control of winemaking, especially the management of alcoholic fermentation of sugar-rich musts and the control of oxidation during the process.

Conclusion: Reducing ethanol of wines and increasing their acidity are good examples of novel techniques of interest in the context of climate change. Other strategies are still under study to adapt winemaking practices to changes in grape composition.

Significance and impact of the study: Membrane-based technologies can be used to reduce the ethanol content of wines or to increase the acidity. Microbiological strategies will also be soon available for winemakers.

Keywords: Climate change, winemaking, yeast, alcohol, acidity

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Introduction

The major expected effects of climate change are an increase in temperature and changes in rainfall patterns and incoming radiation. As a consequence, vine phenology and grape composition at harvest should be dramatically modified. The main consequences on grapes are more sugar and less organic acids; aromas and phenolic compounds of wines will also be affected.

Excessive alcohol in wines exerts a number of negative effects that raise microbiological, technical, sensory and economic challenges. First, because ethanol is a chemical stress factor for yeast that is often the underlying cause of sluggish or stuck fermentation. Second, because excessive ethanol levels also impair the sensory quality of the wine by increasing the perception of hotness and by altering the perception of wine aroma complexity (Goldner *et al.*, 2009). Today, wines with moderate ethanol levels are often preferred, in accordance with health prevention policies.

Consequently, reducing alcohol levels in wine has inspired considerable efforts in the past decade and remains a major challenge for the coming years. Different approaches to reduce alcohol levels in wines have been proposed at all stages of the winemaking process.

Some viticultural strategies are promising. Thanks to classical breeding research programs, different new grape varieties were created by successively crossing *Muscadinia rotundifolia* and 4 different *Vitis vinifera* cultivars. Such varieties reach full maturity with lower sugar content (i.e. 180 g/l) (Aguera *et al.*, 2010). Two of these new varieties are now being tested in the experimental vineyard of Inra Pech-Rouge at a 1-ha scale. Another advantage of these new grape varieties is their natural resistance against powdery and downy mildew, thus preserving environment from pesticide use.

In a shorter-term perspective, several physical techniques for dealcoholization have been developed (Schmidtke *et al.*, 2012). Another prospect is the development of yeasts with reduced alcohol yield, which is both very promising and challenging (Tilloy *et al.*, 2015).

High pHs are more and more common, in particular in regions located at low latitudes, and acidification may become inevitable for the process (effectiveness of SO_2, avoidance of oxidation, etc) and with regard to organoleptic properties. Addition of tartaric acid is often used but with inconsistent results. Membrane-based technologies have been developed to decrease the pH of wines by removing potassium content (Lutin *et al.*, 2010) and more generally to control wine pH. Besides these new technologies, adapting winemaking practices may be an effective way to counteract the effects of changes in grape composition. This is particularly the case for fermentation management and oxidation control.

Microbiological strategies to reduce ethanol content of wines

1. Reducing ethanol yield of *Saccharomyces cerevisiae*

The yeast *S. cerevisiae* has been the subject of intensive research for metabolic engineering. Strong fundamental knowledge of its genetics, physiology, systems biology and genomics has facilitated its use as a metabolic engineering platform (Nevoigt, 2008; Borodina and Nielsen, 2014). These approaches have been widely used to optimize various traits of interest in the field of food and fermented beverages. In the recent years, reducing ethanol yield has been one of the major targets.

The rate of conversion of sugars to ethanol presents only minor variations between strains of *S. cerevisiae*. Hence, to decrease the ethanol production in this yeast, it is necessary to reroute the flux of carbons to other pathways and to the production of other secondary metabolites. However, there are several constraints: it is essential to maintain the redox balance, to avoid the production of compounds that could affect the organoleptic quality of the wines, and to preserve yeast performance.

To achieve this goal, numerous metabolic engineering strategies have been implemented, such as the expression of a NADH oxidase and a NADPH-dependent lactate dehydrogenase, and the overexpression of *GPD1* (reviewed in Tilloy *et al.*, 2015). Among those various strategies, rerouting carbons towards glycerol has emerged as the best option to reduce ethanol yield (Michnick *et al.*, 1997; Remize *et al.*, 1999; Cambon *et al.*, 2006; Varela *et al.*, 2012).

In *S. cerevisiae*, glycerol plays major roles in redox homeostasis and osmotic stress resistance as it is the main compatible solute in yeast (Blomberg and Adler, 1989). Glycerol is usually found in wines at concentrations ranging from 5 to 9 g/l.

As a proof of concept, wine yeast strains overproducing glycerol and 2,3-butanediol, a polyol with no sensory impact on wines, with a lower ethanol yield and without accumulation of unwanted byproducts have been successfully constructed by metabolic engineering strategies (Ehsani *et al.*, 2009). These strains have the potential to decrease alcohol levels in wines by up to 3% (vol/vol). In recent years, due to the poor public acceptance of genetically modified (GM) strategies, alternative strategies such as evolutionary engineering have been favored.

Evolutionary engineering has proven to be successful to reshape yeast metabolism (Figure 1). The concept of adaptive evolution is that microorganisms tend to evolve their intrinsic characteristics to adapt to new conditions. During this process of evolution, random genetic mutations occur, and if a selection pressure is applied, strains having one or several beneficial mutations in the selective medium will dominate in the culture medium and can thus be selected. This approach is based on the extended cultivation of a strain in controlled selective medium to select for natural genetic variants having beneficial mutations under the conditions used. Since the emergence of mutations is a rare event, several hundred generations are usually necessary before observing an evolution, which can last several months.

Adaptive evolution of a commercial wine yeast strain (Lalvin EC1118®) has been carried out to divert yeast metabolism towards increased glycerol and lower ethanol production using hyperosmotic stress as selective condition. Serial transfers were performed during 300 or 450 generations using either sorbitol or KCl as osmostress or salt stress agent.

The approach with KCl stress succeeded in generating strains with redirection of carbon flux towards glycerol. After 200 generations under KCl stress, a first adaptation was detected and the observed increase in glycerol production was maintained after 250 and 300 generations.

The evolved strains showed a gain in fitness conferred by a better viability under salt stress and carbon starvation conditions, which was correlated to a greater glycerol production.

Detailed characterization of the KCl-evolved mutants during wine fermentation showed that the evolved strains have substantial changes in central carbon metabolism. Carbons are rerouted towards glycerol, succinate and 2-3-butanediol at the expense of ethanol and without the accumulation of undesirable compounds such as acetaldehyde, acetate and acetoin.

The concentration of the most abundant byproducts after 30 days of fermentation was determined (fermentation was conducted on a synthetic medium containing 260 g/l glucose and 210 mg/l of assimilable nitrogen, as described by Bely *et al.*, 1990). Carbon and redox balances were close to 100% for all strains. All evolved strains produced glycerol at concentrations 48 to 67% higher than that produced by Lalvin EC1118®, and the ethanol content in the synthetic wines was reduced by 0.45 to 0.80% (vol/vol). The evolved strains also produced larger amounts of succinate and 2,3-butanediol. In contrast, unlike previously described with engineered strains, no significant changes in the production of acetate and acetoin by the evolved strains were found, and the production of acetaldehyde remained in the range of the level found in wines. The evolved strains exhibited an overall decrease in fermentation performance in comparison to the ancestral strain but were nevertheless able to complete the fermentation. The final cell populations were the same between the ancestral strain and these two evolved strains.

To understand the metabolic changes underlying these phenotypic differences, the transcriptome and the endo-metabolome of the evolved mutants and of the ancestral strain were compared. The mechanisms underlying the overproduction of glycerol in the evolved mutants remain intriguing. Indeed, yeast facing severe KCl stress could have evolved the structural or regulatory genes that are related to glycerol metabolism. However, no significant changes in the transcription levels of genes involved in glycerol metabolism or in the high osmolarity glycerol (HOG) pathway and its target genes that would explain the increase in glycerol production were found. This suggests that glycerol overproduction is not mediated via increased protein

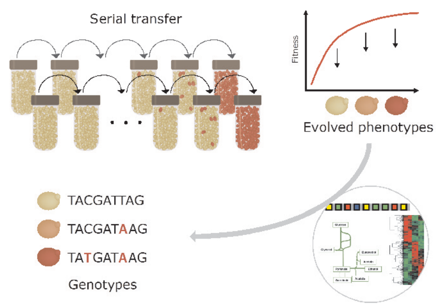

Figure 1. Evolutionary strategy by serial batch cultivation.
Prolonged cultivation is used to enable selection for successive mutations that confer a selective advantage (as higher biomass, growth rate or survival). Evolved phenotypes are analyzed by genome sequencing and a combination of omics to identify the underlying mutations. The mutations can be reconstructed in the ancestral background to validate their impact on the evolved phenotype (Tilloy *et al.*, 2015).

synthesis of the glycerol pathway enzymes. Mutations in the evolved strains affecting post-transcriptional mechanisms could also modulate the reaction rates of glycerol production. The increased glycerol production could also be due to a global metabolic effect resulting from metabolic flux changes in central carbon metabolism.

The exact nature of the factors that caused the metabolic rearrangements in the evolved strains during the evolution experiment is difficult to identify. Whole genome sequencing revealed many changes between the ancestral and the evolved strains. Among these, a loss of heterozygosity (LOH) was observed in the evolved strains, particularly those selected in the late phase of the evolutionary process. Furthermore, in addition to the study of single-nucleotide polymorphisms (SNPs), quantitative trait locus (QTL) approaches were implemented to identify the molecular basis of this new phenotype. Bulk segregant analysis (BSA) was designed confronting a pool of segregants from an evolved high glycerol-producing strain to a pool of segregants derived from the parental strain. Candidate genes were identified and are currently under functional validation to confirm their implication in the phenotype.

To further increase the ability of the evolved strain to produce glycerol and to decrease its ability to produce ethanol during alcoholic fermentation, this strain was further subjected to conventional breeding. To this end, about 150 haploid yeast spores from the evolved strain K300.1(b) were generated and haploid strains of opposite mating type having the highest capacity to produce glycerol were selected. Mating between two spores producing 20.9 and 16.2 g/l glycerol during fermentation on MS medium generated a first generation hybrid. After sporulation and spore mating, a second generation hybrid, H2, which produced 16.8 g/l glycerol, was obtained.

To validate the results obtained at laboratory scale, we compared the behaviors and metabolic properties of K300.1(b), H2 and Lalvin EC1118® during pilot-scale fermentation using a Syrah grape must, at 28°C. To avoid stuck fermentation, oxygen and nitrogen were added during fermentation. H2 had a fermentation rate slightly lower than those of Lalvin EC1118® and K300.1(b), but all strains were able to complete the fermentation, despite the high sugar concentration (255 g/l). K300.1(b) and H2 produced more glycerol (14.1 g/l and 17.9 g/l versus 10.8 g/l) and slightly more succinate than Lalvin EC1118®. The ethanol contents of the wines produced by K300.1(b) and H2 were reduced by 0.6% (vol/vol) and 1.3% (vol/vol), respectively. The production of acetic acid by the evolved and hybrid strains was greatly reduced compared to that of Lalvin EC1118®.

The selected final strain was assessed at pilot scale on different grape musts during the 2013 and 2014 harvests. The wines obtained contained between 0.6 and 1% (vol/vol) less alcohol and very little volatile acidity. By contrast, their total acidity was consistently higher, which has a strong interest since the increase in wine alcohol content is most often associated with high pH (Tilloy *et al.*, 2015).

In summary, the results obtained in grape must at pilot scale confirm the metabolic shift of the evolved strain and show a greater metabolic reprograming of the hybrid derived from the evolved strain.

This study demonstrates that a combination of adaptive evolution and breeding strategies is a valuable alternative to rational engineering for the generation of non-GM, low ethanol-producing yeasts.

2. Reducing ethanol yield by using hybrids and non-*Saccharomyces* yeast

Interestingly, other species belonging to the *Saccharomyces* group (*S. uvarum* and *S. kudriavzevii*) differ in the metabolism for glycerol production and transport, NADH balance, and acetic acid production (Masneuf-Pomarède *et al.*, 2010; López-Malo *et al.*, 2013; Pérez-Torrado *et al.*, 2016). These species can be used as an original genetic material to get non-GM strains showing a partial reduction in ethanol content. However, their lower ethanol tolerance was clearly a discriminative trait, distinguishing these species from *S. cerevisiae*. As industrial winemaking may reach final ethanol content higher than 15° TAV, the low ethanol-producing strains must also have a strong ethanol tolerance. The benefits of hybridization have been described in a large range of plant and animal species in an agronomical context. One of the most striking consequences of hybridization is the phenotypic superiority of hybrids over their two progenitors (i.e. heterosis) (Lippman and Zamir, 2007). Hybridization may also confer an improved phenotypic stability over environmental change (i.e. homeostasis) (da Silva *et al.*, 2015).

Hybrids

In the *Saccharomyces sensu stricto* clade, hybrids can be easily obtained both at the intra or interspecific level allowing yeast improvement. Recently, we obtained a collection of 4 *S. uvarum* and 7 *S. cerevisiae* parental strains and all their 55 possible hybrids. The parental strains came from different beverage industries (wine, distillery and cider) as well as from nature isolates.

Fermentations were carried out at 2 temperatures (18°C and 26°C) in Sauvignon banc grape must containing 188 g/l sugar. The phenotypic distribution of 35 traits, i.e. fermentation kinetics, yeast population, aromatic profiles and fermentation products, was measured for the entire data set in triplicates (da Silva *et al.*, 2015). The ethanol/sugar yield (g ethanol/g of sugar consumed) was computed for the strains that achieved alcoholic fermentation leaving less than 1.6 g/l of residual sugar. Within strains of the same group, this parameter showed very low variability (CV <1.2%), underlining the strong robustness of this trait. Nevertheless, at 18°C we observed a significant reduction of ethanol production for the *S. uvarum* group with an average of 0.30% (vol/vol) reduction compared to the *S. cerevisiae* group (parental and intraspecific hybrid strains). The interspecific group showed an intermediate ethanol/sugar yield with some individuals producing 0.30% (vol/vol) less ethanol than the *S. cerevisiae* group mean. Interestingly, these interspecific hybrids have higher fermentation performances than the *S. uvarum* group due to the positive contribution of the *S. cerevisiae* genome. Within those hybrids, we selected one background of particular interest, EU23.

This hybrid was further tested in synthetic medium with higher sugar content (230 g/l) and compared to 8 strains of commercialized starters. At 18°C, EU23 showed a 0.34% (vol/vol) ethanol decrease related to glycerol overproduction (9.0 g/l compared to 6.5 g/l for the commercial strain group). As previously observed in Sauvignon blanc, the temperature slightly impacts the ethanol/sugar yield and only a difference of 0.15% (vol/vol) ethanol was observed in the same media at 28°C. In different red grape musts (Merlot and Cabernet-Sauvignon) this level of discrepancy (ranging between 0.15 and 0.32) was also observed at laboratory and at small pilot scale (30 l).

These results confirmed the interest of interspecific hybrids for lowering alcohol production. However, the reduction level obtained is not yet sufficient to guaranty a relevant result for an industrial application. Adaptive evolution experiments are now carried out by applying different osmotic stresses to this interspecific hybrid.

Non-*Saccharomyces* yeast

Several non-*Saccharomyces* yeast, such as *Torulaspora delbrueckii*, *Schizosaccharomyces pombe*, *Kluyveromyces* spp., *Issatchenkia* spp., *Zygosaccharomyces bailii*, etc, may also contribute to wine fermentation.

One species, *Candida zemplinina*, was evaluated and compared to *S. cerevisiae*. Forty-eight *C. zemplinina* isolates (mainly from Bordeaux must and also from Hungary and Italy must) were used. Three *S. cerevisiae* were also tested for their fermentation performance. Fermentations were carried out in pasteurized Merlot grape must containing 240 g/l sugar at 4°C.

In pure cultures, *C. zemplinina* yeast resulted in stuck fermentations, confirming the low fermentation capacity of this species reported in the literature. The *C. zemplinina* group possessed a low alcohol/sugar yield, 12% less compared to *S. cerevisiae* strains, which can be partially explained by the overproduction of glycerol.

We investigated the possibility of using *C. zemplinina*, as a partner of *S. cerevisiae*, in mixed fermentations by inoculating 10^7 viable cells/ml *C. zemplinina* with 2.10^6 viable cells/ml *S. cerevisiae*. In addition, sequential fermentations were inoculated

Table 1. Sequential cultures of *C. zemplinina*/*S. cerevisiae*.

Musts were inoculated with *C. zemplinina* (10^7 viable cells/ml), followed by *S. cerevisiae* (2.10^6 viable cells/ml) after 24 or 48 hours of fermentation. Means of triplicate fermentations ± SD. *: Significantly different from pure *S. cerevisiae* culture.

	Sequential cultures *C. zemplinina*/*S. cerevisiae*						Pure culture
	Strain 401 Seq 401		Strain 629	Strain 261	Strain 153	Strain 278	*S. cerevisiae*
	24h	48 h	48h	48h	48h	48h	FX10
Ethanol (%)	13.16 ± 0.07*	13.52 ± 0.18*	13.46 ± 0.05*	13.41 ± 0.08*	13.51 ± 0.04*	13.01 ± 0.04*	13.91 ± 0.00
Res. sugar (g/l)	0.87 ± 0.14	0.90 ± 0.20	0.90 ± 0.10	1.33 ± 0.75	0.83 ± 0.06	0.95 ± 0.07	0.95 ± 0.07
Yield (g/g)	0.43 ± 0.00*	0.45 ± 0.00*	0.44 ± 0.00*	0.44 ± 0.00*	0.45 ± 0.00*	0.43 ± 0.00*	0.46 ± 0.00
Vol. acidity (g/l)	0.45 ± 0.01*	0.84 ± 0.15*	0.83 ± 0.07*	0.76 ± 0.04*	0.81 ± 0.07*	1.01 ± 0.06*	0.31 ± 0.04
Glycerol (g/l)	13.03 ± 0.87*	14.72 ± 0.80*	15.36 ± 0.95*	15.76 ± 0.62*	15.21 ± 0.46*	15.76 ± 0.01*	7.30 ± 0.48

with *C. zemplinina* (10^7 viable cells/ml), followed by *S. cerevisiae* (2.10^6 viable cells/ml) after 24 or 48 hours of fermentation.

All mixed cultures were able to complete fermentation. In our conditions, no significant differences in ethanol production were observed between *S. cerevisiae* FX10 Zymaflore culture and co-cultures (simultaneous inoculations) (data no shown). In contrast, sequential fermentations resulted in reductions of ethanol production from 0.39 to 0.90% (vol/vol) (Table 1). Note that for the sequential culture with *C. zemplinina* 401 a higher reduction is observed when *S. cerevisiae* is added earlier during fermentation. The best sequential multistarter was *C. zemplinina* 401 with *S. cerevisiae* added after 24 hours of fermentation.

Subsequently, a sensory evaluation was performed. Mixed culture wines were judged to be significantly different from those made by single *S. cerevisiae* culture. The latter scored better, while those made by the mixed cultures showed high sulfur off-flavor.

Further investigations are required to clarify the molecular mechanism underlying the reduction of ethanol production in *C. zemplinina* species. Its use in sequential culture appears promising regarding low-ethanol production, but an important effort has to be done to propose *C. zemplinina* strains with neutral impact on the organoleptic perception of wine.

Technological strategies

Microbial strategies still require additional studies to be fully effective when several new techniques and winemaking practices are – or will soon be – available to help the winemakers to correct the physico-chemical and sensory balances of wines.

1. Membrane-based technologies

Non-porous membrane technologies, due to their potential control by on-line sensors and their narrow specificity, provide powerful tools for the tuning of alcohol content and pH.

Reducing wine alcohol content

The removal of ethanol from wine after fermentation can be achieved by using various technologies like membrane filtration, distillation under vacuum or atmospheric pressure, spinning cone columns, adsorption (on resins, silica gels or zeolite), freeze concentration, evaporation and extraction using organic solvent or supercritical solvent. Among all these methodologies, semi-permeable membranes by which alcohol can be separated from wine have been applied for several years (Aguera *et al.*, 2010). Among membrane filtration techniques, reverse osmosis (RO) is the most used technique as it works at low temperatures with few negative effects on wine sensory attributes. Since water is removed along with alcohol, it should be added back to the treated wine or added to wine before RO application. Since addition of water to wine is prohibited in many countries, the resulting permeate should be coupled to steam distillation or membrane contactor technologies to separate water from ethanol (Bes *et al.*, 2010). However, regardless of the method used, the extent of aroma loss and change in flavor components increases with increasing amount of ethanol removed (Aguera *et al.*, 2010). Therefore, the sensory properties and acceptability of ethanol-removed wines may differ based on the final ethanol concentration and consumer preferences.

Adjusting wine pH

Tartrate stabilization by electrodialysis is the original «control and monitoring» electro-process, since it combines a mathematical model to calculate and predict the conductivity reduction needed on any wine to guarantee tartrate stability at -4°C/24.8°F for 6 days. Based on the same device, but using different membrane stacks, on-line acidification or de-acidification by bipolar electrodialysis system under enological conditions removes either potassium or organic acids from grape must or wine (Escudier and Le Gratiet, 2012). Depending on membrane type and process selected, it is possible to achieve either (1) the combined extraction of anions and cations to exactly reach the desired level of tartrate stability, (2) the exclusive extraction of cations to accurately adjust wine pH by a desired pH reduction, or (3) the exclusive extraction of anions to reduce wine acidity and increase the pH.

To decrease potassium content and consequently pH, an electro-membrane process with bipolar membranes has been successfully tested in wine (Lutin *et al.*, 2010). The influence of these processes on taste perception (sourness, bitterness, astringency) was investigated. Decreasing wine pH by 0.4 points using an electro-membrane technique significantly reduced the bitterness and enhanced the acidity of red wines, while no effect on astringency was observed (Samson *et al.*, 2009; Caillé *et al.*, 2011). Tannin composition was not modified by the electro-membrane treatment. 3.5 pH wines presented lower levels of monomeric anthocyanins but showed higher color intensity than 3.9 pH wines. These changes reflect a higher rate of conversion of monomeric anthocyanins to derived pigments at the lower pH

Table 2. Comparative data of different treatments for dealcoholization of a wine from 14% (vol/vol) to 12% (vol/vol).

IO: Inverse Osmosis, D: Distillation, NF: Nanofiltration, MC: Membrane Contactor.
Italicized values = values estimated by calculation (Bes *et al.*, 2010).

	IO-D	NF-D	IO-MC	NF-MC
Volume of permeate to be produced per liter of wine (%)	~ 25	~ 18	*~ 50*	~ 30
Volume of water needed for the treatment (l water / l wine)	0	0	0.45	0.3
Nature of the co-product (effluent)	Alcohol ≥ 92% (vol/vol)		Alcoholized water (IO: ~ 4% (vol/vol), NF: ~7% (vol/vol))	

value. Whether these reactions are related to changes in taste properties (especially reduced bitterness of the lower pH wine) remains to be investigated (Müller *et al.*, 2007).

Bipolar membrane electrodialysis as well as use of anionic resins reduce the mineral content of musts, in particular NH_4^+ (Bouissou *et al.*, 2014). Therefore, acidification of musts that exhibit a low content of assimilable nitrogen may require nitrogen supplementation to avoid slow fermentations.

These new processes recently obtained OIV approval and are now authorized in Europe (reg. UE N°53/2011).

2. Control of key winemaking operations

Fermentation

One of the main concerns for enologists during winemaking is to ensure steady and complete fermentation so all the sugars in the must are converted to alcohol. When sugar concentrations are up to 250 g/l, achievement of complete fermentation is challenging and necessitates an optimal management of yeast nutrients.

Combining addition of ammoniacal nitrogen and oxygen is very efficient because of the positive effects of oxygen on yeast survival and of nitrogen on yeast activity (Sablayrolles *et al.*, 1996). However, this addition has to be correctly timed, i.e. at the start of the stationary phase, when about 5% ethanol has been produced (Blateyron and Sablayrolles, 2001).

Casalta *et al.* (2013, 2016) highlighted the interaction between grape solids (the main source of lipids) and assimilable nitrogen content, pointing out the importance of taking into account the balance between assimilable nitrogen and lipids for controlling fermentations during white winemaking. Thus, the strategy to control the alcoholic fermentation should not only take into account the addition of oxygen and nitrogen but also the lipid status of the must.

Soubeyrand *et al.* (2005) showed the advantage of adding protective nutritional elements during the rehydration phase. The yeast protector releases specific micronutrients and micro-protectors that move to the active yeast enhancing its effectiveness during alcoholic fermentation (Salmon and Ortiz-Julien, 2007). The micronutrients (vitamins and minerals) allow the yeast cells to reactivate their internal metabolism. The micro-protectors (specific sterols and polyunsaturated fatty acids [PUFA]) gradually integrate into the yeast cell membrane (Luparia *et al.*, 2004), strengthening it and facilitating exchanges with the exterior, thereby preventing the loss of the cellular material.

Oxidation

After the break of grape berry cell compartmentation during the various technological operations (de-stemming, pressing, crushing, etc), the dissolution of oxygen in the must leads to several oxidation reactions which modify, to varying degrees, the initial chemical composition of the must. This cellular disintegration brings together the substrates for oxidation – the native phenolic compounds of the grape –, oxygen and the enzymatic polyphenoloxidase activity (PPO) of the grape. The color of the must then changes to more of less pronounced brown tones with frequent changes in transparency (Cheynier *et al.*, 2010) and aroma (Hoffman *et al.*, 1996).

In the current context of decreased SO_2 effectiveness (reduction of the doses combined with pH increase of the musts), the behavior of the grape PPO activity during the winemaking process was recently studied (Frissant *et al.*, 2012; Sire *et al.*, 2016). This work led to new information on protection against oxidation during pressing, i.e. (1) the total inerting of a pressing system such as developed by certain manufacturers can be advantageously replaced by a reduction in the temperature of the grape harvest and its preservation during pressing and (2) the quality increase of the end juices of pressing can also be obtained by specific cooling of the grapes with a very strong sensory gain.

The use of inactivated yeasts enriched in glutathione during alcoholic fermentation was also studied in order to protect rosé and white wines from oxidation during wine aging (Aguera *et al.*, 2012). Aging of the corresponding wines in accelerated oxidative conditions or in standardized conditions clearly evidenced a protection of such treated wines against oxidation, from both a sensory and a chromatic point of view. This effect was particularly emphasized for the conservation of odorant varietal thiols.

In the last several years, it has been demonstrated that yeast cells, even in a non-viable physiological state, could exhibit a superfluous oxygen consumption capability, related to a mild oxidation of cellular lipids (Salmon, 2006). Such a potential of oxygen consumption by non-viable yeast cells was therefore applied for the protection of wines against oxidation during storage and/or aging. Yeast derivatives were therefore applied at enological doses on white wines stored under different conditions (with and without SO_2 protection). The obtained data suggested that such specific selected inactivated yeast could represent an innovative solution for the protection of wines against oxidation during storage and aging when compared to SO_2 addition in the protection against oxidative evolution of stored wines (Sieczkowski *et al.*, 2016a, 2016b).

Conclusion

Many different strategies can be used to adapt winemaking to consequences of climate change on grape composition. Some of them are already functional while others are still under investigation. The objective is not only to correct 'defaults' such as high ethanol concentrations or low acidity, but also to look for optimal strategies integrating viticultural and winemaking approaches to optimize wine quality.

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Climate change and adaptation: Alsace and Loire Valley vintners' challenging point of view[1]

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Abstract

The article reports an interview enquiry among 71 wine professionals, mostly vintners in Loire Valley and Alsace. The sample vintners are longstanding observers of the effects of climate change on their vines and wines and have considerable experience in adaptation since they adapt every year to climate change. Yet their analyses of climate change effects and adaptation differ substantially from the scientists'. When asked about climate change effects, they report the usual expected climate change effects but do attribute them to the technical change in the last 30 years rather than to climate change. According to them, the technical change has transformed the wine-growing practices and led to a decrease in yield, which explains the higher berry sugar content, and earlier harvest date, which in turn is accountable for the aromatic changes and a certain loss of balance in the wines. Then the vintners conceive adaptation in a variety of ways, which feed important disputes among them. Adaptation can be seen as (i) compensation practices oriented by a predefined rigid objective, (ii) a more flexible development carer of the vine and, more recently, (iii) a new challenging view where it is up to the vine to adapt. This last way consists in sheltering the vine from excessive climatic hazards, help it buffer its reactions to its environment, become resistant and produce a stabilized terroir quality wine.

Keywords: Vintners' perception; adaptation; climate change; technical change; terroir quality

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The perception of climate change by the « actors »

Why should we care about the actors' perception of climate change? Aren't the climate scientists' and agronomists' results a reliable source of information? Yes they are. Yet the vintners can bring interesting additional information. In France, certain vintners have a longstanding experience in this regard; they have filled detailed climatic records and observations in connection with their vine development since decades, sometimes a century[2]. They also make precise observations regarding the changes occurring in their vineyards at a very small scale, a vine stock or even some of its leaves.

Their observations can help survey global warming progresses and provide detailed accounts of its effects on the vineyards. As professionals, the vintners are indeed often attentive observers of all kinds of events and changes occurring within their vineyards. Furthermore, they must adapt every year to climatic changes, which makes them experts in climate change adaptation.

We can add another important reason for turning towards vintners for effects of climate change: as emphasized by some scholars (Jones *et al.*, 2005), they may consistently vary with viticulture practices. So experienced vintners, cultivating their own vineyards, appear as interpreters of climate change effects worth of interest, namely because they have a consistent knowledge of their own viticulture practices.

We have conducted a field study mainly in two northern French vineyards, Alsace and Pays de Loire, based on interviews with vine-growing, wine-making and wine trade actors. From August 1, 2012 to February 6, 2015, we interviewed 71 persons who responded favourably to our request. They were mostly independent vintners, cooperative members or employees, all making Protected Denominations of Origin wines (PDO), with some PDO syndicates, National Institute of origin and quality (INAO) employees, journalists, wine retailers and researchers (Table 1). The interviews usually lasted from half an hour to four hours (1H45 to 2H00 in average), sometimes followed by a visit of the vineyard with the vintner. Some interviews continued on the Internet (by email) or were repeated up to 5 times, so as to provide a more detailed understanding of the interviewee's point of view. The vine-growers have been chosen so as to be representative of the diversity of the profession: independent vintners and cooperative members, running small or big wineries, with different interests or conceptions regarding wine quality. We did not meet many cooperative members; very few accepted the interview so we turned to the staff of the cooperative and their presidents. As for any field interview, our sample gathers mainly vintners who felt interested by the question and had something to say to the researcher. As is common in France, the interviewed vintners had rather small wine estates ranging from 7 to 40 ha. The study concentrated on Loire Valley and Alsace. To contrast the specificities of our sample, we added a few interviews from countries or regions (5 interviews in Languedoc and 3 interviews with winery technical staff members in Morocco and Argentina) with different wine production structures (Morocco and Argentina with large vineyards of hundreds of hectares), with different concerns regarding wine quality, and in southern locations said to face stronger climate change effects, namely drought (Languedoc in France, Morocco and Argentina). These interviews are not meant to account for the situation in locations foreign to the sample, but to help grasp some of the peculiarities that any sample necessarily has or not.

Vintners' observations & analysis

Nearly all interviewed vintners note an increase in climatic hazards, but no global warming effect. At first view they even appeared to be quite climate sceptics, corroborating the results of a questionnaire enquiry in Spain (Alonso and O'Neill, 2011)[3].

This result would be erroneously related to the geographical implantation of Alsace and Pays de Loire. Indeed, they all noted changes usually associated by scientists to global warming (Seguin and Garcia de Cortazar, 2005; De Orduna, 2010): an earlier harvest date, an increase in berry sugar content, aromatic changes, and sometimes (not for all wines) a decrease in acidity. With a few rare exceptions, they claimed these changes were above all due to technical or even commercial changes.

These vintners are therefore not climate sceptics, but critical observers of the changes occurring within the vineyards. In their interpretation, it is mostly the technical change aiming at quality improvement, which started in the 1990s and spread throughout French vineyards, promoting lower fruit load and better grape ripening, that is responsible for the increase in sugar and the earlier harvesting date. All

[2] The three vintners interviewed in Morocco and Argentina complained about the weather, which was never as good as they wish, but did not share any sound analysis of climate change effects on their vines. A reason for this can be that they did not enjoy any such long-lasting experience.

[3] More than 50% of the vintners said they were climate sceptics.

Table 1. List of interviewees

	Others	Loire Valley	Alsace	Languedoc
Independent vintner	3 (2 Morocco, 1 Argentina)	22	16	1
Cooperative or cooperative federation Director or representative			2	1
Cooperative member			1	
Interprofessional organization		1	1	1
Wine trade	3		2	
Certification (ODG/INAO, independent firms)	3	4	8	1
Research and technique, oenology consultant		1	4	1
Journalist	2		1	
Total = 71	11	25	30	5

these changes lead to a certain loss of balance in the different maturation processes regarding phenols, sugar and aromas. Since they relate these changes to technical change, they try to adjust their vine-growing and wine-making practices. Some of them start to mention - with extreme precaution - a possible increase in their yields (well below the PDO limits), so as to achieve a better convergence between the different maturation processes. Their main preoccupation is to not jeopardize the grape and wine quality they aim at.

Ligerian and Alsatian vintners do not stress any global warming effects; nevertheless, they underline an important increase in climatic hazards, referring namely to recent exceptional vintages such as the very hot 2003 and 2009, the very cold and late 2010, or 2013 disturbed by unusual heavy hail episodes. Some scholars may associate it to climate change, others to the vintners' increased concern for viticulture practices and the management of their impact on the vines. For many of the sample vintners these increased hazards are again not related to global warming: they follow cyclic variations, as shown by their weather records as well as their global assessment of the vintages, with succession of good and bad decades. They do not see anything new or unique here, and therefore do only exceptionally[4] include climatic change considerations when they plant new vineyards. Considerations about the height of the vines, their pruning, and the configuration of the canopy are always related to quality objectives.

Whatever the reason for their focus on climatic hazards, it stresses a particular interest towards viticulture practice adaptation[5], Yet this adaptation is a yearly adaptation, which resorts to an extensive array of old and new practices such as the thinning of leaves, the increase of the soil surface albedo, the management of the water resources, and an increasing number of simplified cultivation techniques aiming towards non-cultivation techniques. The interviews gather a long list of such techniques, as well as demands for enhanced flexibility in PDO regulations or new plant material. But these demands diverge considerably according to each vintner; they even raise considerable disputes among them. Some would ask for old traditional vine varieties "adapted" to the local conditions, while others expect new vine varieties or clones resistant to climatic hazards. All these answers depend strongly on the vintners' understandings of quality and adaptation.

How do the vintners adapt to the changes?

All of the interviewees showed considerable interest in quality as well as strong discrepancies in the right understanding of PDO quality and the right way to adapt to climate variations so as to obtain a good PDO quality wine. Three different interpretations of quality can be drawn from the interviews. The first two result from a 15 to 20 years growing controversy on PDO quality. The third one could bring a new turn to the debate.

1. Adaptation as an objective oriented compensation or a development oriented support

The first two interpretations commonly regard viticulture and climate adaptation as vine development management, but diverge in the way to achieve it. They can be compared with two opposite views on pedagogy. In the first one, the objective to

[4] Two of the interviewed vintners had experimental vineyards with southern grape varieties. One saw it as a global warming change adaptation trial.

[5] A few interviewees, mostly from the cooperative side, asked for economical adaptation, such as government subsidies or the alleviation of AOC production requirements they have been asking for a while.

be reached is predefined and firmly holds during the apprenticeship, and the efficiency of the learning techniques is constantly reassessed. They are improved or changed as often as necessary so as to get as close as possible to the objective. In the second one, the objective is constantly revised so as to adapt not only to the pupil achievements but also to the pupil itself, to its capacities and interests.

Like the first teachers, vintners try to reach a production objective relatively firmly predefined according to marketing strategies and an estimation of the firm production capacities. The viticulture practices are assessed, revised and adapted according namely to the firm capacities, its work force, farming tools and financial possibilities.

Their opponents criticize this way of adapting. They denounce an excessive concern for the customers and their changing tastes and a lack of terroir authenticity. They plead for a higher respect of the vines "terroir expression", which includes variations with the different vintage climatic conditions. They argue that "terroir expression" cannot be predefined and even less adapted to market fashions. On the contrary, it has to adapt to the development of the vine all along the vegetative cycle. They wish to grant a major role to the vine in the realization of the achieved quality. In order to do so, they resort to particular viticulture techniques: non-cultivation or as much simplified as possible viticulture practices and oenological techniques. They are not reluctant to vine-growing or wine-making technique changes. But they require these innovations to be terroir oriented. As a consequence, they prefer to turn to neglected or complementary PDO traditional vine varieties, instead of varieties invented from scratch.

2. Deciding about PDO quality

These two points of view feed important debates among vintners namely because each implies a different compromise on technical constraints and quality achievements. Supporters of the first point of view, whose adaptation can be related to a compensation strategy because it aims at compensating for the lacks and failures in vine development, repeatedly ask for increased flexibility in the production constraints so as to be able to always better achieve their production objective whatever the vintage conditions. Supporters of the second point of view, on the contrary, emphasize the need for strong constraints on viticulture techniques and most of all on oenological practices so as to make sure that the vine development is not distorted and the wine processing does not spoil the grape quality with excessive vintner interventions. They conversely request flexibility in the achieved result, as it is the terroir and therefore the vine in its vineyard and climate that decides quality has to be, not the vintners.

Although not always the case, the first view is usually supported by a higher number of vintners. But numbers are not a good clue for settling the dispute. Indeed, both views are necessary for a collective successful adaptation: PDO names must be relatively rigidly tied to a certain identifiable PDO quality so that the name makes sense for wine drinkers. Yet the referred PDO quality must also be flexible enough so as to enable adaptation to a constantly changing world.

A third interpretation of adaptation, which is still in the making, has recently appeared and could bring new arguments to the dispute. This third group of vintners agrees with the idea that the PDO quality has to be protected from the "erroneous" first vintners' conception of PDO terroir quality and emphasizes as well the need to enhance the vine contribution to its definition. However, for them, the best way to avoid distortion in the yearly adaptation process is to foster another conception where the vine itself adapts to the vintage conditions, with least possible vintners' interventions.

3. It is up to the vine to adapt!

This third growing interpretation of adaptation cannot anymore be compared to a teaching method where the pupil would define the goal to achieve during the apprenticeship. The vine is no more comparable to a pupil; vintners rather see it as an expert and the one who knows what the right quality is and who produces it, although, of course, the vine is unable to make it explicit. The vintner is still necessary in the achievement of terroir wine quality. He must help the vines produce the best terroir quality grapes, Yet in doing so he stay in the background not only regarding the quality objective to achieve but also the way to produce the quality.

Besides simplified cultivation techniques, which protect the wine terroir quality from excessive vintner practices, they try to shelter the vines from excessive climatic hazards by encouraging the vines to develop their roots in the deeper soil layers far from the changing superficial conditions, with stable water supply, temperatures and environment. They carefully avoid high yields, which "make the plants sensitive to changes". Regarding the upper aerial part of the plant, they try to restore and develop the ecological network tying the plant to its environment and its web of interactions, which help the vine to buffer and compensate for the changes occurring in its environment. They look for "resistant" plants whose stabilized quality is an important sign of the capacity of the vine to adapt by itself to the changes. Organic or biodynamic viticulture techniques have long been an important inspiration for the vintners aiming at protecting the vine or terroir expression because these environment-friendly techniques were *a priori* also terroir- and vine-friendly. They even explore further this technical pathway, by developing the ability of the vines-in-their-terroir to "resist", that is to keep being true to themselves in a changing world.

4. A new turn in controversies on acceptable quality variability

Quality variability is of main concern for the study of climate change impacts on vine and wines: indeed, PDO regulations include restrictions not only on production practices but also on the resulting wine quality. Therefore, any change in grapes or wines may induce problematic wine variability.

Wine diversity issues are not strictly restricted to climate change. The management of wine variability has a longstanding history, which resulted in several laws, among which the 1905 law on fraud suppression (Loubet and Ruau, 1905), the creation of new wine definitions and classes, such as the Denominations of Origin ("simple" AO) with the French 1919 law (République Française, 1919), then the Controlled Denominations of Origin (AOC) (République Française, 1935), later transformed by the 2008 European reform (European Commission, 2008) in Protected Denominations of Origin (PDO)[6]. AOC and then PDO regulations never explicitly defined what wine quality should be. At most they partially specified it by a series of analytic criteria and allowed range. In 1970, a European directive (European Economic Commission, 1970) generalized a compulsory taste agreement. This still in force organoleptic test only assesses broad categories allowing for wide variation: "Art. 11 1.b. The organoleptic test shall concern colour, clarity, smell and taste."

Divergent views on the good ways to achieve AOC and then PDO quality, conflict on the acceptable taste diversity of the wines. Climate change and the increased vintners' focus on good climate adaptation fuel this controversy among the PDO vintners.

The last development of better terroir-oriented vine-growing and wine-making practices is about to bring a new contribution to the controversy on authentic terroir quality production by introducing a new criterion in the assessment of good adaptation practices: the stabilization of terroir expression in the wines. Yet the decrease in diversity that can be expected from this focus on quality stabilization only regards each vintner and its own brands, not the whole PDO production.

But the answer these last vintners are elaborating regarding adaptation issues is both challenging and innovative as it turns to nature and not any more only to human technology to produce an adapted behaviour.

Conclusion

Neither global warming nor climate change is such a big issue for the AOC vintners of our sample. The major changes they observe in their vineyards converge with the expected global warming effects. But in their view, they are the result of the practice change they have themselves fostered. Therefore and quite logically, they do not see adaptation as an issue; on the contrary, they claim they actually cope with these changes and do not ask for extra help. The impediments they underline regarding their vine-growing and wine-making activities remain quite the same and mainly depend on the way to deal with terroir quality and terroir-quality suited practices.

These results may surprise and one could insist in interpreting them as the consequence of the northern location of our sample vineyards, Loire Valley and Alsace. But vintners are not climate sceptics, though they could seem to be in the interviews. They do not disagree on the existence of changes, only on their presumed cause and relative importance. When, with reasons, climate scientists take for granted the existence of a climate change and look for its effects, vintners start, on the contrary, from the changes they observe and try to tie them to a plenty of possible causes, some of them, they assume having much higher effect than climate change. They add that they could hardly notice such a slow mean change in temperatures as claimed by scientists when they have to deal with much higher yearly variations.

The purpose of a perception survey is also to check for climate awareness (Lemos *et al.*, 2012; Mosedale *et al.*, 2016). Should we conclude that the interviewed vintners are not aware enough of climate change and most of all of global warming? Is it a risk that they will continue to contribute to global warming? A large part of the interviewed vintners

[6] For a more detailed account of the history of acceptable diversity assessment and management, please refer to Teil (2015).

were quite green house gas (GHG) emissions aware, and of these, all the vintners engaged in the second (development carers) and third (vine-delegation) modes of adaptation. Some of them even had CO_2 emission free wineries.

A minority of actors interviewed during this study showed more conventional answers. Cooperative presidents, PDO representatives, retailers, and a few vintners following compensation adaptation strategies agreed, sometimes strongly, with that climate change had important effects. They emphasized thus the need for subventions or PDO technical constraints alleviation or for increased pressure on GHG emission-generating practices. Did they do so because they were "rightly" seeing the "true" effects of climate change while the first vintners' perceptions were biased by vested interests or a bad and selective memory? Scientific claims are not only "facts"; they also raise interests. We have insisted on the vintners' perception precisely because they do not follow the main stream without being climate sceptics. They not only propose an interesting reflexive critique on climate change causes but also add a detailed interpretation of the notion of "adaptation", which do not resort to any stabilized reference. Such a reference allows scientists to calculate and make climate change "visible". But the choice of such a reference favours climatic considerations disregarding other sources of changes. This is precisely what the sample vintners point out: climate scientists work hard to raise a climate cause and then forge a series of expected impacts. But if you proceed reversely, observing the changes and trying to associate them to a cause, the number of candidate causes will immediately be overwhelming and their selection will require tough work. The confirmation and measurement of climate change through observation is a difficult task because the stabilization of the world necessary to identify changes only due to a climate cause is not straightforward.

Last but not least, how far can or should we generalize our sample results? Again, this question supposes a rather rigid world with actors having fixed interpretations, observations and practices. This is far from being the case. Actors do not stop changing their ideas or theories, interpretations. They accumulate observations, they discuss their implications with colleagues, and they change their practices according to their assessments. As a consequence, the proportion of vintners invested in the development of resistant vines may change from time to time, from vineyard to vineyard according to their results and ability to argue and prove the PDO terroir quality of their wines, which is not easily foreseeable. Yet a more detailed account of the variety of the vintners' accounts for climate change effects and adaptation practices would certainly bring a better knowledge of the "needs" of the vintners and the innovations they may find acceptable or useful.

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Adaptation strategies to climate change in the French wine industry: The role of networks connecting wine producers and researchers

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Abstract

In this paper we analyze the adaptation strategies of wine producers in three French vineyards (Bordeaux, Champagne, Languedoc) and how these strategies can be supported by the construction of networks between wine producers and R & D organizations. We characterize these strategies by the perception of the climate change (CC) issue, the development of new practices and the construction of networks. We carry out surveys in the three regions on both producers (87) and R & D actors (94); we describe winegrower strategies and researcher involvement in CC issues; and we test different factors that can explain these strategies by using four econometric models. Our main results show that both the perception of CC by wine producers and the network they built to improve their knowledge are different according to the region. Personal trajectory (education, professional experience, etc.), production patterns (conventional, organic) and previous networks also influence the adaptation strategies. On the other side, researchers' involvement in knowledge production on "wine and CC" is not sufficient to improve winegrowers' adaptation to CC. The contribution of researchers to CC adaptation is influenced by their research field, their regional location, their organizational affiliation and, above all, their involvement in regional networks including various intermediaries, with a specific role of wine inter-professional organizations.

Keywords: wine, climate change, adaptation, research, network, France

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Introduction

Recent work in economics suggests that firms' adaptation to climate change (CC) will depend on their ability to obtain, use and share knowledge on climate at a regional or local scale (Rosenzweig and Wilbanks, 2010). CC is beginning to be well known at a global scale (at least for temperature trends and their impacts), but its specification at local level remains uncertain despite the fact that it is crucial for firm strategies, particularly in industries like construction, transport or agriculture (Viguié *et al.*, 2014). This is the case for the wine industry, already impacted by CC (Holland and Smit, 2010; Jones and Webb, 2010; Ollat *et al.*, 2016). In France, CC impacts are observed in all the vineyards, with different intensities and consequences, but also with common traits: advancement of phenological stages and harvest dates, increase in the alcohol degree of wines, loss of acidity and modification of aromatic profiles, more frequent water stress, particularly in the Mediterranean area, etc.

The literature in economics and sociology suggests that building operational knowledge on both local impacts of CC and adaptation solutions can be based on two types of networks: i) local exchange of information between wine producers (peers), structuring networks and "communities of practices", which have been demonstrated to be crucial for the adaptation to other challenges such as quality and environmental issues (Touzard, 2011; Chiffoleau and Touzard, 2014; Compagnone, 2014; Montés Lihn, 2014); and ii) regional collaborations between universities, research centers, technical organizations and wine producers, which can improve the resilience and competitiveness of wine clusters (Fensterseifer, 2007; Giuliani *et al.*, 2010; Boyer, 2016).

In this paper we focus on this second type of networks. We analyze the adaptation strategies of wine producers in three French vineyards (Bordeaux, Champagne, Languedoc) and the links they establish in their region with R & D actors. The originality of our work is to approach these strategies and links from a double survey in each region: on the one hand from a sample of wine producers and on the other hand from a sample of R & D actors. We describe the wine producers' strategies and the R & D actors' involvement, and we explore the factors that can explain these strategies by using econometric models. We will show that (i) the links between wine producers and researchers, involving intermediaries, play a key role in adapting to CC, and (ii) these networks mainly depend on the personal characteristics of both the wine producers and the researchers, and on a set of regional aspects including the role played by the inter-professional wine organizations.

Theoretical framework

2. Adaptation strategies for climate change

Adaptation to CC can be broadly defined as "the set of actions and processes that can modify natural and human systems in response to climate change, in order to reduce its negative effects or take advantage of its positive effects" (Hallegatte, 2009). Different adaptation approaches are possible, depending on whether adaptation is considered as state, strategy, process or capacity (Holland and Smit, 2010; Boyer, 2016). We will take here a strategic definition of adaptation, which relies on "a calculation that projects the actor in the future according to the environment as it is perceived" (Capet *et al.*, 1983). A strategy for adaptation to CC can then be characterized by three dimensions:

i) the **perception of the climate issue** and its translation into objectives. The actor will consider his/her future behaviors and decisions according to his/her perception of the effects of CC (Yegbemey *et al.*, 2013; Van Duinen *et al.*, 2015);

ii) the **actions undertaken** aiming at these objectives. The actions can be investments in infrastructure, adoption of technological innovations or new practices, organizational changes or re-location (Boyer, 2016). They can be reactive or proactive, and may be associated with cost-benefit calculation (De Perthuis *et al.*, 2010);

iii) the **building of social links** by the actor to capture resources (cognitive, economic, physical, etc.) allowing to implement these actions. The access to new knowledge and the need to share experiences put networking at the heart of adaptation (Grin, 2010).

2. Involvement of researchers in adaptation

Combining perceptions, actions and networking, our approach to adaptation first applies to an economic actor, such as a wine producer or, by extension, a wine company.

But adaptation is not only driven by economic actors. It implies interactions between many actors within a sector or a territory, in particular the actors involved in the innovation system (Malerba, 2002; Touzard *et al.*, 2015). In the vine and wine innovation system, some actors are specialized in the production of knowledge (Boyer, 2016). Researchers, and more broadly R & D actors, can help economic and political agents to identify the effects of CC, to test different adaptation options, and to propose tools that simulate or explore scenarios for the future (Rosenzweig and Wilbanks, 2010; Barbeau *et al.*, 2015; Delay *et al.*, 2015).

Researchers may thus be considered as actors of adaptation to CC in the wine sector (Giuliani *et al.*, 2010; Boyer and Touzard, 2016). It is possible to analyze their involvement in the adaptation strategy by referring to the three dimensions mentioned above: (i) their perception of CC and the place of CC in their research topics; (ii) their research projects and their production of knowledge on CC (publications); and (iii) the links they construct not only with their colleagues, but also with economic and political actors, for example through formal (partnership projects) or informal collaborations (personal links). These links may be direct or indirect via intermediaries (Klerkx *et al.*, 2009). The ability of the researchers to build links with wine producers can be seen as a condition for adaptation, perhaps as important as their scientific publications.

We therefore suggest that adaptation to CC in the French wine industry depends on the combination of i) the adaptation strategies of the economic actors, ii) the involvement of R & D actors (researchers) in the production of knowledge about vine/wine and CC, and iii) the networks built between these two types of actors.

3. Exploring the factors of adaptation strategies

Several factors are likely to influence the adaptation strategies of economic actors. Analyzing these factors is crucial to propose public policy that could facilitate adaptation. These factors include those generally identified by the literature on innovation or risk management (Touzard, 2014): economic characteristics of firms (size, access to funding, nature and range of productions, competitiveness, etc.); human and social capital of the entrepreneur (skills, links with peers and researchers, participation in collective actions, etc.); resources and institutions provided by the local/regional context (Yegbemey *et al.*, 2013; Chiffoleau and Touzard, 2014; Van Duinen *et al.*, 2015; Van Gameren *et al.*, 2015).

As we also consider the involvement of R & D actors in the adaptation to CC, we must take into account the factors that influence these involvements. Recent studies on innovation have focused on these factors, including in the wine sector (Giuliani *et al.*, 2010; Boyer, 2016): the personal characteristics and trajectory of the researcher (sex, age, experiences, number of publications, etc.); his/her location in a region offering different infrastructures and externalities for research; and the characteristics of the organization in which he/she is working (public or private, teaching, research or development, etc.) (D'Este and Patel, 2007; Boardman and Ponomariov, 2009). The field of research can also influence the relations between researchers and economic actors. For instance, a researcher working on computer programming will be less likely to have links with wine producers than one working on vine canopy management.

The challenge of innovation system analysis is then to identify different types of factors that influence different types of actors who can interact in the same industry. Some factors may be common to all actors, while others may be specific to each actor.

Method

1. Approach based on two categories of actors

We study adaptation to CC from two categories of actors: the wine producers and the R & D actors (researchers, engineers, technicians). We started by describing the strategies that contribute to adaptation: for the winegrowers, we describe their perception of CC and the actions and networks they plan to adapt; for the R & D actors, we examine their contributions to research on CC and the links they establish with the heads of the wine companies. In a second step, we tested the factors, common or specific, which can explain these strategies, generally referring to the actors' location, their personal characteristics, and the characteristics of their activity and their organization (wine farm vs research unit). Finally, we sought to link the strategies of these two categories of actors and to compare their factors, in order to have a systemic approach of adaptation and to test the assumption that "the collaborations between researchers and entrepreneurs play a key role in building adaptation to CC".

2. Choice of three wine regions

We selected three important French wine regions (in terms of value of production) representing different climatic conditions: Aquitaine (Bordeaux) for the oceanic climate; Languedoc (Montpellier) for the Mediterranean climate; and Champagne (Reims) for a more continental climate. Climate scenarios and their impacts differ according to each region. The Languedoc wine industry is already marked by difficulties linked to more pronounced water stress and to high alcohol levels and decreased acidity in wines; Aquitaine seems to have benefited for the moment from CC but the region will approach

Mediterranean climatic conditions with worrying effects on the wines coming from the current varieties (Merlot in particular) ; and Champagne, probably less impacted by water stress in the medium term, could be subject to summer heat waves and higher disease pressure (Briche, 2011). Beyond these climatic changes, the three regions concentrate most of the R & D on vine and wine. They also refer to different kinds of wines, farms and professional organizations (Boyer and Touzard, 2016).

3. Definition of areas for adaptation

Several areas have been defined for adaptation, corresponding to both the areas of action/innovation for the winegrowers and the areas of research or experimentation for the researchers :

1. Plant material, that is to say the potentialities of already cultivated vine varieties (in different regions) or new ones (hybrids in particular) to deal with the consequences of CC ;

2. Vine plot management (vine architecture, technical practices, soil and water management, etc.) adapted to CC, for example to promote grape freshness, limit evapotranspiration or improve the resilience of vines facing climatic risk ;

3. The control of parasitic pressure, caused in particular by new climatic conditions, through monitoring and methods to treat/control parasites ;

4. Oenological practices that can correct the effects of CC on wine quality (reduction of alcoholic degree, acidification, aromatic profile, etc.) ;

5. Spatial and economic strategies allowing producers not only to establish their vineyards in new soil and climate conditions, but also to innovate and organize themselves to improve their competitiveness under CC.

4. Wine producer surveys

A first set of surveys was carried out in 2015 in the three regions with 87 wine producers : 28 in Champagne, 29 in Bordeaux and 30 in Languedoc. The surveys focus on winegrowers producing Appellation d'Origine Contrôlée (AOC) wines, in order to have common structural conditions. The sample was drawn from the contact lists of AOC unions and controlled by three variables : relative economic size (two categories of firms in each region) ; conventional or organic grape production ; and spatial distribution within each region (to avoid a concentration bias in a subarea).

The questionnaire takes into account the general characteristics of the wine producer and his/her farm, his/her perceptions of CC and its effects, the actions undertaken in each of the five adaptation areas, and the requests for advice carried out or envisaged (by area), in order to reconstitute his/her egocentric advice networks (Touzard, 2011).

5. R & D actor surveys

A second set of surveys was carried out in 2015 in the three regions with actors of the main research and experimentation organizations working on vine and wine : INRA, CNRS, IRSTEA, universities and agronomic schools, IFV, chambers of agriculture, wine inter-professional organizations. A sample of 94 stakeholders was surveyed from the lists of researchers or engineers working on vine and wine in all of these organizations : 41 in Languedoc-Roussillon (30 researchers and 11 engineers), 34 in Bordeaux (25 researchers and 9 engineers) and 19 in Champagne (7 researchers and 12 engineers).

The questionnaire takes into account general information on the career and activity of each actor, the importance he/she gives to CC in his/her work (on a scale ranging from 1 to 5), his/her scientific productions and projects in each field of adaptation and how he/she disseminates the information to winegrowers (personal links, joint projects, conferences, publications in technical journals, etc.).

Bibliometric analyzes completed these surveys to specify in each region the scientific outputs on the different areas of adaptation (Boyer, 2016).

6. Econometric models

For the winegrowers, we retain two dependent variables, one on the perception of CC, the other on the actions undertaken. For each, we tested explanatory variables, leading to two econometric models :

The first model is a multiple regression that aims to determine the factors that influence the perception of winegrowers on CC : PERCC, evaluated from 1 to 5.

$$PERC_{ki}=\beta_0+\beta_1(UTH)_i+\beta_2(FORM)_i+\beta_3(SEX)_i+\beta_4(ANC)_i+\beta_5(SAL)_i+\beta_6(STAJSUP)_i+\beta_7(PCA)_i+\varepsilon_i$$

The second model is a logistic function that aims to explain the probability that the winegrower innovates to adapt to CC : P (INOVCC).

$$LogP(INOVCC)= 11-[PINOVCC=1)]=\beta_0+\beta_1(UTH)_i+\beta_2(EVOLCA)_i$$

Table 1. Variables used to describe and explain the strategies of winegrowers

VARIABLES TO BE EXPLAINED		EXPLANATORY VARIABLES			
		Economic characteristics	**Region**	**Personal characteristics**	**Relations with:**
Actions to adapt : INOVCC	**Perception of CC : PERCki**	Amount of work in winegrowing firm: UTH	REG : (3 categories)	Sex: SEX	Chamber of agriculture: PCA
		Evolution turnover: EVOLCA	Languedoc: LR	Seniority: ANC	Inter-branch organization: PINT
		Type of wine: BIO	Champagne: Ch Bordeaux: Bx	Educational background: FORM	Suppliers: PFOUR
		BIO=1 if Organic wine		Participation in wine events: SAL	Laboratory of oe nology: PEXP
		BIO=0 if Non-organic wine			Peers: PCOL Researchers: PRECH University interns: STAJSUP

$$+\beta_3(FORM)_i+\beta_4(SEX)_i+\beta_5(ANC)_i+\beta_6(STAJSUP)_i +\beta_7(PCA)_i+\varepsilon$$

The explanatory variables are given in Table 1. The egocentric networks have been constructed by selecting six categories of actors to which the producer has asked advice (explanatory variable) or expects to seek advice in the future (strategic variable) for adaptation to CC.

For the researchers, two dependent variables were also selected, leading to two other econometric models :

The first model is a multiple regression that explains the involvement of the actors in research on CC : ICC, evaluated from 1 (no involvement) to 5 (main research topic).

$$ICC_{ki}=\beta_0+\beta_1(DREC)_i+\beta_2(STRUCf)_i+\beta_3(SEX)_i +\beta_4(AGE)_i+\beta_5(INTERN)_i+\beta_6(PRO)_i+\varepsilon_i$$

The second model aims to explain the proximity of the R & D actors to the winegrowers. It is evaluated by using as proxy the number of heads of wine companies cited by each R & D actor, called "number of contacts" : CAVI.

$$CAVI_{ki}=\beta_0+\beta_1(DREC)_i+\beta_2(STRUCf)_i+\beta_3(SEX)_i +\beta_4(AGE)_i+\beta_5(INTERN)_i+\beta_6(RESO)_i+\varepsilon_i$$

The explanatory variables are given in Table 2.

Results

1. Adaptation strategies of the wine producers

Among the 87 winegrowers, 66 (76 %) state that the consequence of CC is already visible at the farm level. There are no significant differences between regions. Winegrowers are able to identify the effects on the average of three different areas of action, but these areas depend on the region (Figure 1). In Languedoc, winegrowers feel more concerned by water stress and the increase in alcohol degree, in Bordeaux by inter-vintage differences and vine management, and in Champagne by pest pressure. These challenges have been recently associated with arguments and discourses about CC.

59 % of winegrowers report having already innovated to adapt to the effects of CC : 67 % in Languedoc against 57 % in Champagne and 52 % in Bordeaux. To adapt to CC, winegrowers mainly plan to mobilize the networks already in place with the actors of the regional innovation system for other issues (productivity and quality improvement, marketing, environmental norms, etc.). This result

Table 2. Variables used to describe and explain the involvement of R & D actors in adaptation

VARIABLES TO BE EXPLAINED	EXPLANATORY VARIABLES			
	Organization	**Research domain**	**Region**	**Personal characteristics**
Investment in research on CC : ICCi **Relations to producer :CAVIi**	STRUCf STRUCf=1 if Research institution STRUCf=0 if Development organization	DREC: (5 categories) Plant material: Mat Plant management: Con Plant diseases: Lut Oenology: Eno Economic and spatial strategies: Strat	REG: (3 categories) LR: Languedoc Ch: Champagne Bx: Bordeaux	Age: AGE Sex: SEX Seniority: ANC Educational background: FORM Participation in project on CC: PRO Wine network member: RESO International experiences: INTERN

covers a wide range of winegrowers, including those who consider that the effects of CC are not yet observable.

On the other hand, the advice network that is projected for adaptation varies according to the region (Figure 2). In Languedoc, winegrowers will mainly seek advice from colleagues, chambers of agriculture and suppliers. In Bordeaux, they prefer seeking advice first from suppliers, then from chambers of agriculture and research centers (ISVV). Finally, the winegrowers of Champagne declared that they will request information on CC mainly to their inter-professional organization (CIVC) and private experts.

2. Factors explaining the adaptation strategies of the wine producers

The results of the first econometric model (Table 3) show that variables related to inherited advice networks and personal characteristics influence the perception of CC (PERCC):

1. The economic characteristics of firms do not influence the perception of CC;

2. Winegrowers who used to contact chambers of agriculture, take trainees, and participate in trade fairs or events related to innovation feel much more concerned about CC. One can see here an important effect of existing network converging with individual dispositions to curiosity and novelties;

3. The winegrower's seniority and experience play a positive role in the perception of CC. Here we can see the possible influence of "learning by doing" and the need of historical references on climate trends and variability.

The results of the second model (Table 3) allow to identify the factors influencing the wine producers' decision to adapt (INOVCC):

1. The economic characteristics of firms do not influence innovations;

2. Growers who used to seek advice from chambers of agriculture and take trainees are more likely to adapt to CC than others;

3. The level of education/training and the experience in viticulture positively influence the decision to innovate in order to adapt to CC;

4. Growers who develop organic or biodynamic viticulture are more involved in new practices that they refer adaptation to CC.

3. Involvement of R & D actors in adaptation

Among the 94 R & D actors located in the three regions, 42 (45 %) are directly involved in "vine, wine and CC" research or experimentation programs and 27 (30 %) declare that this question is central to their activity. There are no significant differences between the three regions. This confirms that CC has become one of the main issues in the scientific community working on vine and wine, or at least that CC constitutes an important argument that justifies research in many disciplines working in this sector. The bibliometric analyzes show that the researchers have similar level of publication in each region, but that the topics of their research are clearly different. Languedoc researchers particularly publish on topics related to plant material, vine management and irrigation, those of Champagne on vine diseases, and in Bordeaux on oenology and vine management.

On average, each R & D actor mentioned 26 frequent contacts with wine producers, but with a large deviation expressing two contrasted modalities: a high number of contacts given by actors of inter-professional organizations (in particular CIVC) or chambers of agriculture; a low score expressed by INRA researchers who just mentioned an average of 12 contacts.

4. Factors explaining the involvement of R & D actors

The results of the third econometric model (Table 3) show the influence of the following variables on the contribution of R & D actors to the knowledge on "vine, wine and CC" (ICCki):

1. The level of academic excellence (publications, diploma) and the personal characteristics (age, sex,

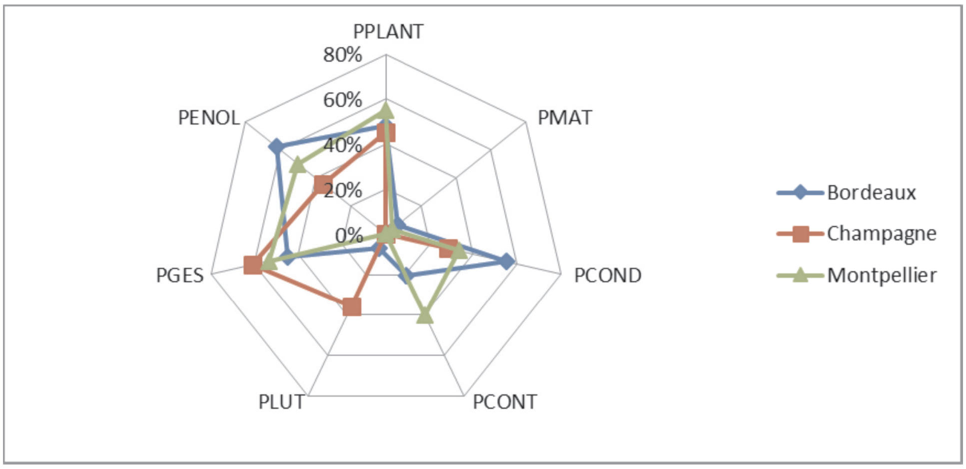

Figure 1. Perception of climate change by winegrowers in 3 regions
PENOL: Perception of CC effects on oenological characteristics - PPLANT: Perception of CC effects on planting conditions PMAT: Perception of CC effects on plant material - PCOND: Perception of CC effects on vineyard management - PCONT: Perception of CC effects on water stress - PLUT: Perception of CC effects on new disease pressures - PGES: Perception of CC effects on harvest dates

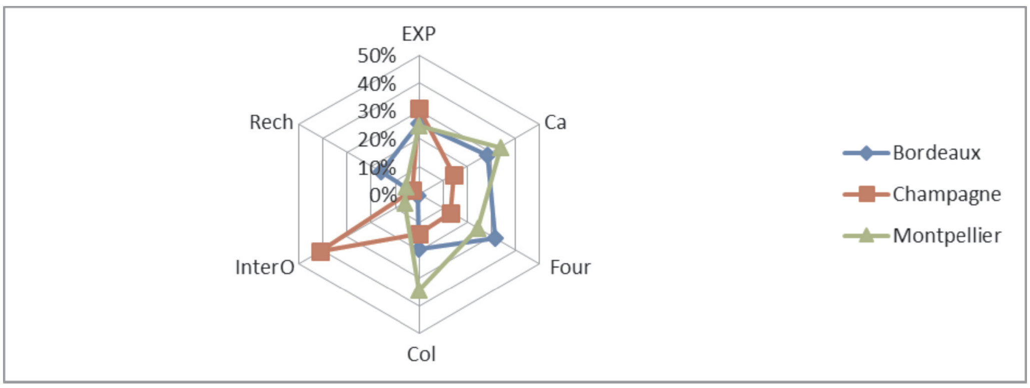

Figure 2. Sources of information for winegrowers on climate change and adaptation
Chamber of agriculture: CA Inter-branch organization: INTERO - Suppliers: FOUR Laboratory of oenology: EXP Peers: COL Researchers: RECH

etc.) of the R & D actors do not play a significant role in their involvement in the CC issue;

2. On average, researchers (from INRA, universities, etc.) integrate more CC issues into their work than experimenters and engineers (from IFV, chambers of agriculture, etc.). This confirms that the CC issue remains pushed/promoted by the scientific community;

3. R & D actors from Languedoc-Roussillon and Bordeaux are more involved in the CC theme than those in Champagne (regional effect);

4. The field of research is an important factor. R & D actors working on plant material or vine management declare to invest more in the production of knowledge about CC than those working on pest management, oenology or spatial and economic strategies.

The results of the fourth econometric model (CAVI) show that the same factors have influence on the ability of R & D actors to forge links with the wine producers, but mainly in the opposite direction (Table 3):

1. The level of academic excellence and the personal characteristics of the R & D actors do not play a significant role in their contacts with the wine producers;

2. Engineers and experimenters are closer to winegrowers than are the researchers, which is coherent with the mission of each activity. Development actors are supposed to work on dissemination and thus to have more contacts with winegrowers;

3. In Champagne, R & D actors are closer to winegrowers than in the other two regions, but this regional factor is correlated with the higher weight of the Champagne inter-professional organization (CIVC);

4. R & D actors who work on plant material and oenology have less contact with the winegrowers than actors who develop research and experimentation on vine management or economic strategies.

Discussion and conclusion

1. Convergence between the perception from economic actors and the orientation of research

While there is no clear regional difference in the intensity of CC perception for the winegrowers and the level of scientific production for the researchers, the content of this perception and production is quite different from one region to the other. The comparison between the results of the two surveys thus reveals a convergence in each region between the CC perception of the winegrowers and the themes developed by the researchers on vine and wine. The winegrowers of Languedoc say they are mainly confronted with problems of water stress, those of Bordeaux to oenological challenges, and those of Champagne to problems of pest development. These issues and needs expressed by the economic actors globally correspond to the orientations of the researchers' work in each region. This convergence can proceed from common awareness facing the same regional context or from previous collaborations and mediated interactions in each region. Anyway, it is a favorable condition for further adaptation to CC and the improvement of interactions between researchers and wine producers.

2. Economic conditions vs personal characteristics for adaptation

Adaptation to CC is supposed to have strong economic implications and to rely on cost-benefit analysis. It could therefore be argued that the economic characteristics of firms would be decisive, such as research on this topic in economics and management. Our study shows, on the contrary, that i) neither the size nor the economic evolution of firms influence adaptation to CC and ii) researchers studying socio-economic questions are less concerned, even if they have more contacts with winegrowers. This suggests that adaptation to CC remains perceived as a technical issue and not yet as an economic strategy. This can also be explained by the fact that the effects of CC have not yet sufficiently affected the competitiveness of wine firms.

On the other hand, individual characteristics appear to be important to explain both the adaptation strategies of winegrowers and the involvement of researchers in these adaptations. The level of education/training of the wine producer and his/her seniority (including his/her experience in the management of climatic variability), as well as his/her egocentric advice networks determine the strategies of adaptation. For the researchers, these personal aspects are somewhat less obvious but they can be found in their scientific discipline, their previous participations to research projects on wine and CC, and above all their individual initiatives.

The weakness of economic determinants and the weight of individual factors have been largely shown in the case of the emergence of innovations, carried out by risky entrepreneurs or developed in niches where the actors generally have economic and non-economic motivations (Touzard, 2014). It can therefore be argued that adaptation strategies (including perception, action and networking) are in an early stage for both economic and R & D actors.

3. Central role of advice networks in adaptation

Finally, our work confirms the role of the relations between research and economic actors in the adaptation of the wine industry to CC.

From the winegrowers surveys we showed the requests for advice for CC adaptation are strong in the three regions and concern different fields, with differences in content and sources of advice. The presence of trainees emerges as a key and original factor in the three regions, indicating the importance of the links with agricultural higher education; the chambers of agriculture and the suppliers are relevant in Languedoc and Bordeaux; the inter-professional organization and the private councils dominate in Champagne; and direct links with a research organization are only mentioned in Bordeaux, but in the background. This confirms the importance of intermediaries or "brokers" between research and winegrowers (Klerkx *et al.*, 2009).

From the R & D actors surveys we confirmed that researchers are the most aware on CC but have fewer direct links with the winegrowers than the engineers from chambers of agriculture and inter-professional organizations. This suggests the importance of strengthening cooperation between the various R & D organizations through research project, teaching, event or dissemination. Our succinct approach to networks does not make possible to specify the quality and frequency of the links studied. Some direct links between a researcher and winegrowers can thus play a very important role as a bridge between the two communities of practice (scientists vs producers), as shown in several wine clusters (Giuliani *et al.*, 2010; Chiff<oleau and Touzard, 2014).

The example of Champagne could be analyzed in more detail: the Champagne winegrowers feel more concerned about the CC challenge than those of the other two regions, while Champagne is less affected by CC. Through the inter-professional organization (CIVC), several formal networks (at least 7) deal with areas of adaptation that did not originally concern CC, but progressively integrate this issue (Panigai *et al.*, 2014). This kind of regional organization, which is managed by the economic actors, plays a central role in supporting proactive networks able to make concrete requests for research and co-finance this work.

The existence of formal and informal networks is at the heart of an innovation system (Touzard *et al.*, 2015), allowing cooperation, innovation and

Table 3. Results of econometric models

Winemakers				Researchers			
Perception		Innovation		Investment of researchers in CC		Relations	
PERCC	Coefficient	INOVCC	Odds-ratio	ICC	Coefficient	CAVI	Coefficient
SAL	1.85****	Anc	1.055**	Strucf	0.480**	Strucf	-0.991****
Sex	0.02	Form	2.203***	Mat		Mat	-0.759**
Form	0.11	Sex	0.468	Eno	-1.170***	Eno	-0.299
Anc	0.03**	Stajsup	3.550**	Lut	-1.133***	Lut	-0.659**
UTH	-0.005	Pca	2.898**	Condt	-0.568	Condt	-0.545*
Pca	1.44****	UTH	1.008	Stratloc	-1.272***	Stratloc	
Stajsup	0.67*	Evolca	0.697	Pro	1.273****	RESO	1.239****
				INTERN	-0.167	INTERN	0.093
				Age	0.012	Age	0.012
				Sex	0.260	Sex	0.092
Cons	-0.21	Cons	-1.109	_cons	2.451	_cons	2.491****
Nb of obs	87	Nb of obs	87	Nb of obs	94	Nb of obs	94
R-squared	0.4827	LR chi2(7)	26.05	R-squared	0.4452	R-squared	0.4905
Adj R-squa	0.4369	Prob>chi2	0.0005	Adj R-squa	0.3857	Adj R-squa	0.4359
Prob > F	0.0000	Psuedo R	0.2207	Prob > F	0.0000	Prob > F	0.0000

reactivity in a given wine region. The characteristics of these networks (their structure in particular) may ultimately appear more important than the awareness on issue such as CC. The analysis of the advice networks within a regional innovation system is therefore an important way to better understand and support the process of adaptation to CC in the wine industry.

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Global warming and enological strategies: How to anticipate consumer behavior ?

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Abstract

Abstract: With a changing global climate, the viticulture sector faces many environmental and socio-economic challenges. Given the perennial nature of grape growing, winegrowers will need to develop adaptation strategies that deal with both short-term climate variations and long-term climate changes while accounting for local vulnerability in order to avoid mal-adaptation. Here we aimed to enhance the assessment of climate change adaptation in viticulture by undertaking a local-based approach that specifically focuses on the spatial understanding of local variability in environmental conditions and grapevine behavior, as well as the evaluation of winegrowers' decision-making processes and management practices. The methodological framework used in this study was applied to two regulated wine producing areas located in the Anjou-Saumur wine growing sub-region, France. Results have highlighted the importance of undertaking studies at terroir scales in order to better define the spatial variability of local climate and its influences on grapevine behavior, and frame local climate vulnerability and winegrowers' adaptive processes. Within the context of climate change and the key issues surrounding adaptation, local-based studies should allow a greater understanding of the potential future impacts of climate change and adaptation strategies necessary at different spatial and temporal scales.

Keywords: Climate change, local scale, adaptation, viticulture, vulnerability

[1] Data collected in the course of this study show that the average «alcohol by volume» of wines available on the market increased by 2 degrees between 1985 and 2015 while acidity level decreased by 0.5 g/l H_2SO_4.

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Introduction

It is now widely recognized that global warming is significantly impacting the characteristics of wines in many winegrowing regions around the world (Duchêne and Schneider, 2005; Schultz, 2000, 2010; Jones and Webb, 2010). These changes include the apparent higher alcohol level and lower structural acidity level[1], but also include a large number of more or less readily measurable parameters. This phenomenon stems from modifications in the chemical composition of grapes during overripening. Consequently, the wines made from overripe grapes are consistently characterized by jammy fruit flavors (Pons *et al.*, 2012), reminiscent of the style of wines made in dryer, warmer latitudes.

The extent of these changes will largely depend on the production areas and their respective climatic conditions. Many observers state that this evolution in wine characteristics is not critical «quality» wise and emphasize that the wines have never been as good and balanced as they are today[2]. It is interesting to note that these organoleptic characteristics are currently used to describe the aroma of wines made from late-harvest, overripe grapes (Allamy *et al.*, 2015). Furthermore, some ripening-promoting farming practices, such as repeated leaf thinning and excess green harvesting, can accentuate the intensity of this jammy fruit character while also changing the wine's balance (higher alcohol content, less acidity). In fact, enhanced control of sanitary conditions makes it possible to pick grapes riper than in the past. In all, the wines that are now considered «atypical» in a wine region like Bordeaux are currently on the market, meaning that they are valued by some customers, and even some wine critics[3].

If this current valuation were to be maintained over the long term and were to expand on the markets, global warming would appear as an opportunity for some producers. Otherwise, there could be significant changes in the supply/demand balance on the wine market. For example, if northern wine regions (or even new areas not yet planted to grapes) were to propose wines with lower alcohol level or more freshness, best meeting the expectations of the new generation of consumers, then one would expect southern producers to make agronomic adaptations (*e.g.*, better suited grape varieties) or enological remediation technology to bring wine characteristics back to normal and keep their market shares[4].

This paper reports the findings of two separate experiments aiming to evaluate consumer reaction to (i) «global warming wines» (experiment conducted on commercialized Bordeaux wines) and (ii) enological innovations for reducing wine alcohol content and increasing wine acidity (experiment conducted on commercialized Languedoc-Roussillon wines). An experimental economics approach was used in both cases to assess consumers' preferences and willingness to pay (WTP)[5] for each of the wines proposed in the course of the study. Both experiments were conducted in laboratory (sensory analysis rooms), with WTP being evaluated by a direct (the consumer states his/her WTP based on available wine information) and incentive process (the consumer is encouraged to disclose the truth about his/her WTP). The process is similar in that respect to the one used in the work of Lange *et al.* (2002) and Combris *et al.* (2009) for the wine market. Such process through which the consumer agrees to buy *in situ* a product corresponding to his/her expectations is a powerful tool to determine the truthfulness of his/her answers.

The results of the first experiment initially indicate a significantly greater consumer preference for wine presenting characteristics similar to those expected from global warming over more traditional wine (*i.e.*, of lower alcohol content and higher acidity), but that this preference is highly unstable. It appears that this preference is likely to change over the long term and that saturation effects are felt fairly quickly after repeated consumption. This finding, which supports sensory analysis outcomes in other food areas (*e.g.* Lévy *et al.*, 2006; Köster, 2009), reinforces the concerns mentioned above regarding the supply/demand balance over the long term and leads us to explore enological strategies based on the initial analyses carried out by Urbano *et al.* (2007) and Meillon *et al.* (2010 a,b). Similar to these studies, we did not find any marked consumer preferences in the

[2] See especially http://bordeauxclassicwine.fr/2016/03/le-gout-du-vin-de-bordeaux-deux-millenaires-d-histoire.html

[3] In particular, as noted by most observers, the renowned 1980-2010 wine critic, Robert Parker, had a strong preference for ripe, rich, jammy wines. During that period, he strongly influenced the viticultural methods of a large number of Bordeaux estates in that direction.

[4] Agronomic solutions may include the use of vine training systems better adapted to climate change or grape varieties with lower sugar content (van Leeuwen *et al*., 2013). There are also a large number of enological solutions including the use of wine yeast strains with lower sugar/alcohol conversion efficiency, vacuum distillation, reverse osmosis, or membrane-based processes to reduce wine alcohol level or modify wine acidity (see Aguera *et al*., 2010; Escudier *et al*., 2014; and study coordinated by Teissedre, 2013).

[5] WTP is defined as the maximum price a consumer is willing to pay for a wine, *i.e.*, the price above which he/she will definitely not buy.

Table 1 - Experimental design: overview of the different informational steps ranked by increasing information availability.

Informational steps	Descriptions	Consumer responses
1 - AOC - Vintage	Information common to the four wines on the name of the Bordeaux region AOC and the vintage (2010)	Disclosure of one WTP
2 - AOC - Vintage + **Visual**	Additional color evaluation for each of the four wines	Disclosure of one WTP for each wine evaluated
3 - AOC - Vintage + Visual + **Odor**	Additional aroma evaluation for each of the four wines	Disclosure of one WTP for each wine evaluated
4 - AOC - Vintage + Visual + Odor + **Taste**	Additional taste evaluation for each of the four wines	Disclosure of one WTP for each wine evaluated
5 - AOC - Vintage + Visual + Odor + Taste + **Alcohol level**	Additional information on the exact alcohol level of each of the four wines	Disclosure of one WTP for each wine evaluated

second experiment. Even though the wines proposed showed a wide range of alcohol levels (as sole criterion) or acidity levels (again as sole criterion), there were no significant preferences. This does not mean that consumers are not able to distinguish between the different wines and discriminate them. Rather it shows that the aggregated WTP data mask strong, but highly heterogeneous, individual preferences. This highlights a high degree of consumer segmentation.

In the next two sections, we explain the methodology used for the two experiments. We then conclude by explaining why these experiments should be extended to a more detailed assessment of consumer evaluation of global warming perspectives.

Consumer perception and acceptability of global warming wines

A first set of experiments was conducted in Bordeaux in 2013 with three wines selected from a single AOC (*appellation d'origine contrôlée*) of the Bordeaux wine region and from the same vintage (2010). Although all were considered «typical» of the AOC, they showed large differences in the contrasting «fresh fruits» and «jammy fruits» criteria that we assumed to be markers of global warming. Wine A had the lowest «cooked fruit» intensity, while the diametrically opposed wine B had the highest intensity (wine A also had 13.9% alc.vol. and wine B 15.2% alc.vol.). Wine C had intermediate intensity and an alcohol level of 14.4% vol. Finally, a «pirate» wine A' was made by addition of ethanol (+ 1.3% vol.) to wine A such as to obtain the same ethanol level as wine B.

The recruitment of consumers for the experimental market was conducted by a specialized company based on simple criteria (usual wine consumers/buyers quotas and assurance that these consumers were regular buyers of > 15€ Bordeaux wines). In total, 184 consumers were selected and divided into two groups (G1 and G2) with similar age, sex, socio-professional categories and consumption habits distribution. The two groups were subjected to the same «tasting room» experimental protocol. Group G2 was also familiarized with the «extreme» wines A and B through a home tasting in order to perform a comparative study of these wines. For that experiment, each G2 consumer initially received one anonymous bottle of each wine (labeled A and B). It should be noted that the G2 consumers were at no time informed that these wines A and B were also part of the laboratory experiment, the latter being identical for both group G1 and group G2 in terms of design.

1. Experimental design

Wine assessment by G1 and G2 consumers was carried out in the Bordeaux region in a sensory analysis room (NF – ISO 8589). The wine samples were anonymous (labeled with three-digit codes) and presented in random order. The four wines were presented to each consumer simultaneously.

The proposed experimental design is a 5-step protocol with increasing information availability taking into account the basic wine tasting steps (Table 1). One should note our decision at step 1 to inform the consumers of the name of the selected AOC and the vintage. The objective was to provide a common minimum reference frame such as to minimize cognitive impairment and interindividual differences linked to a fully blinded evaluation. The consumers then evaluated the different wines through visual (step 2), olfactory (step 3) and taste assessments (step 4). In the final step, the consumers were informed about the alcohol level of the wines to

[6] Several methods for measuring WTP can be found in experimental economics literature (*e.g.* Lusk *et al.*, 2011), each with its own advantages and drawbacks. BDM is the most commonly used method by authors since it is easy to understand by average consumers and hence easy to implement in an experimental market.

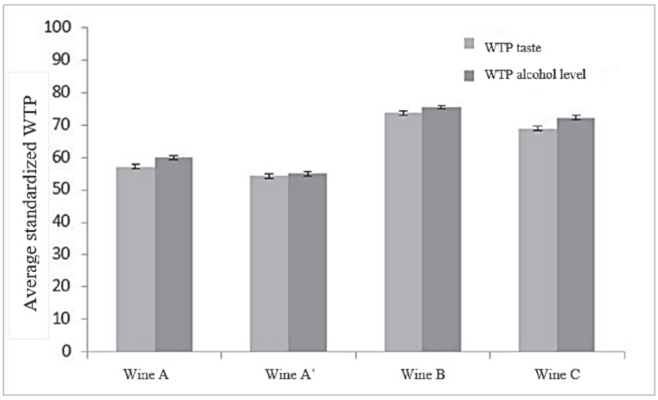

Figure 1 - Average wine-standardized willingness to pay (WTP obtained at the first step of the experiment = 100) for the taste and alcohol level (alcohol by volume) steps.

see how this information could affect their decision and preference ordering.

Each consumer had to disclose his/her WTP at each informational step. Consumers were allowed to change their WTP for a given wine based on incoming information at each new step outlined in Table 1. The method used to measure the WTP was that of Becker, DeGroot and Marschak (BDM; Becker *et al.*, 1964), which consists in randomly drawing a sale price for each wine from a ballot box[6]. One wine (A, B, C or A') and one information situation from Table 1 were randomly drawn at the end of an experimental session. If the consumer's WTP was above or equal to the sale price drawn at random, he/she had to buy the product.

2. Results

Consumers' evaluations of the wines were relatively heterogeneous throughout the 5-step process, with some consumers frequently changing their WTPs (either upward or downward) according to the additional incoming information. Nevertheless, the average step-by-step WTPs show little variation with a relatively low standard deviation (around 5.6). It should also be noted that the WTPs were slightly below market prices (which is common for this type of experiment, see Lusk and Shogren, 2007) but quite consistent (reported WTPs were around 9€). The main conclusion concerns the difference in consumer behavior between groups G1 and G2 at the final stage of the wine evaluation, *i.e.*, step 4 (taste information) and step 5 (wine alcohol content information).

At that stage, wine B (highest alcohol content) was clearly preferred over wine A for group G1. Statistical analyses (ANOVA and Duncan's pairwise comparison test, $p<0.05$) revealed a significant preference for wine B over wine A. The average WTP for the intermediate wine C was intermediate between wine A and wine B. By contrast, the «pirate» wine A' got the lowest WTP, but the difference with wine A was not significant. In other words, wine A' is quite competitive on the market without being considered by G1 consumers as an «outlier» wine. In addition, disclosure of the alcohol level did not significantly impact the average WTPs of the wines (Figure 1). This information did not affect post-tasting consumers' responses in any way.

3. Impact of repeated consumption

It is now well known that repeated exposure to a given product has a significant impact on consumers' preferences: on the one hand, because the complexity of a food product is strongly linked to exposure time, (*e.g.* Berlyne, 1967, and more recently Lévy *et al.*, 2006; Meillon *et al.*, 2010b), and on the other, because repeated consumption leads to a saturation effect (*e.g.* Glanzer, 1953; Rolls *et al.*, 1981; Van Trijp, 1994; Lévy and Köster, 1999).

In our case, we showed how familiarization with the wines challenges the evaluation made by G1 consumers. For group G2, wine A becomes equivalent to wine B and gets a higher average WTP. Wine C still gets an intermediate WTP between wine A and wine B, whereas wine A' is now considered well below and significantly different from the other wines.

The key point is that this *preference reversal* is not specifically related to a greater appreciation of wine A (the WTP for this wine varies by only 6% between the two groups and is not significant). Rather, it is related to a disinterest in wine B, which fell by more than 20% between group G1 and group G2. This loss of interest, measured here at the last protocol step, is in fact observable from step 3 (odor step). Further analysis of hedonic data show that while 63% of G1 consumers preferred wine B, precisely for its «cooked fruit» character, this number dropped to 39% in group G2.

Thus, it can be seen that G2 consumers' preferences changed after repeated exposure to both wines. This is the result of a saturation effect following a repeated consumption of wine B, having a higher

[7] See especially the National Institute for Agricultural Research program on «Quality wines with reduced alcohol level» (VDQA); *http://www1.montpellier.inra.fr/pechrouge/images/vdqa.pdf#page=1.*

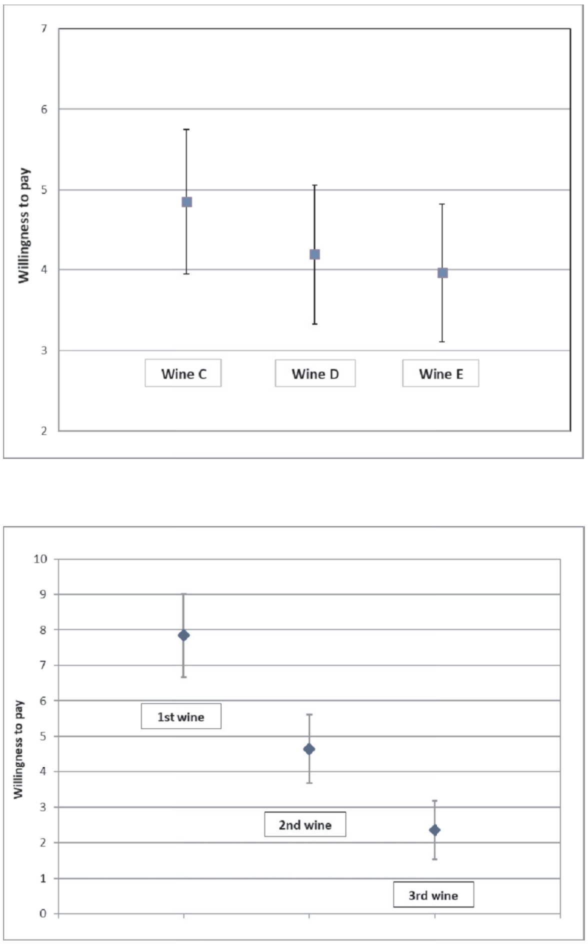

Figure 2 - Confidence intervals (95%) - Willingness to pay classified by wine (a) and by rank (b). Dealcoholized red wine experiment.

alcohol level (15.2% vol.) and more concentration than wine A.

Altogether, these results show that «global warming wines» might be ignored by consumers, at least in the long term; some of the changes in wine characteristics negatively affect wine acceptability.

Consumer acceptance of enological processes

As mentioned above, it is possible, at least technically, to adjust wine alcohol level (alcohol by volume) or pH level (acidity), which are the first and foremost parameters affected by global warming. New enological practices regarding acidification (European regulation EU No 53/2011). This practice, as for dealcoholization, can now be performed at the estate by using a mobile unit. The maximum possible level of correction for dealcoholization is 20% for PGI wines (protected geographical indication), and slightly less (maximum of 2% alc.vol.) for PDO wines (protected designation of origin). In the second

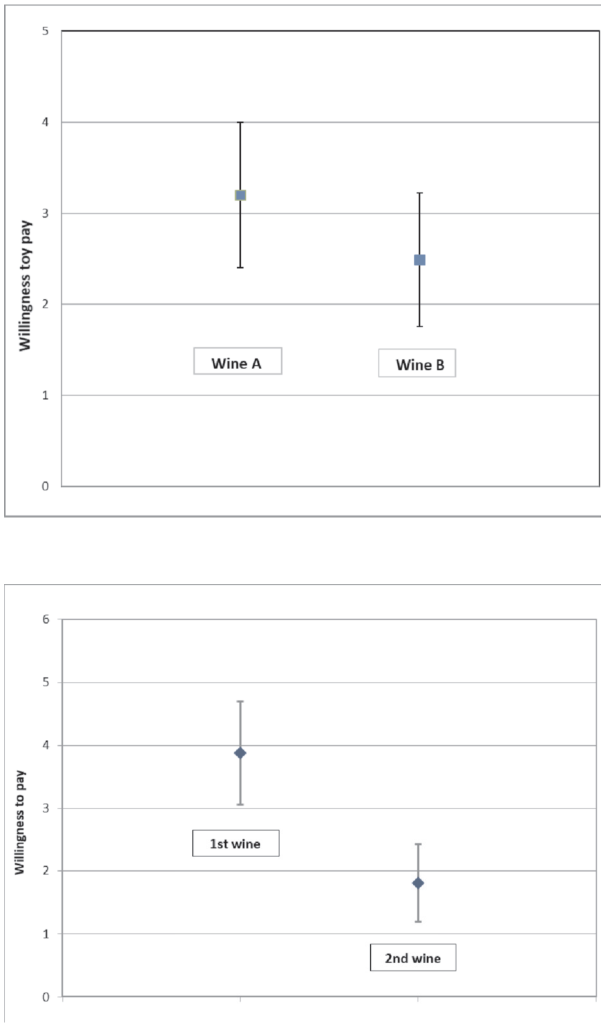

Figure 3 - Confidence intervals (95%) - Willingness to pay classified by wine (a) and by rank (b). Acidified rosé wine experiment.

part of this work, wines made at the experimental station of INRA-Pech Rouge[7] were subjected to partial alcohol reduction (red wines; reverse osmosis coupled to membrane contactors) or acidification (rosé wines; membrane-based pH reduction, Oenodia process) and tested by 60 consumers. These two types of wine were evaluated in 2014 by the same consumers using the same BDM-elicited WTP measures. This time, however, wines were assessed globally (without distinction between the different sensory characteristics) and, as for the previous experimental protocol, using geographical origin as sole wine information.

Three red wines were tested in the dealcoholization experiment: control wine C (14% alc.vol.), wine D (12% alc.vol.) and wine E (10% alc.vol.), with wines D and E being obtained after partial alcohol reduction of wine C. When looking at the experimental market results, the findings are all the more surprising (Figure 2a). Indeed, in this case it is not possible to establish any wine order. The average WTPs and standard deviations are highly consistent, making it impossible to rank the wines. Does this mean that the consumers see no differences between the wines? The answer is «no». Because if we look at the WTP of the first, the second and the third wine of each consumer (Figure 2b), we find a clear distinction between the average WTPs of the first wine (regardless of its alcohol level and different for each consumer), the second wine and the third wine. This means that the innovation is accepted and even preferred by some, but not all, consumers and that each of the wines considered is only a small niche market. The fact that similar results are found in the acidification experiment (Figures 3a and 3b with the control rosé wine - pH 3.57 - and its acidified version - pH 3.41) suggests that companies would be forced into further market segmentation (the women and the young people being more likely to adopt the new enological processes in our experiment), further increasing the (already high) number of products on the wine market.

It would be interesting to compare these consumer results with those of a sensory analysis panel of wine experts. Indeed, wines with high alcohol levels and low acidity have been shown to be perceived as more bitter and, in case of red wines, more astringent (Müller et *al.*, 2007; Samson et *al.*, 2009; Escudier et *al.*, 2011, 2015; Caillé *et al.*, 2015). The visual and olfactory descriptors are also impacted. These sensory characteristics most certainly influence consumer preferences and can partially explain consumer segmentation.

Conclusion

In this paper, we have addressed the challenges posed by global warming to wine consumers, first in terms of changes in the final wine characteristics and then in terms of enological processes likely to be used to adjust to these changes. The WTP methodology has proven to be a powerful analytical tool for assessing consumer preferences and validating individual consumer tastes.

We have demonstrated how established consumer preferences were highly dependent on previous exposure to product. This is especially important in red wines presenting high concentration attributes, where saturation effects may come into play and influence subsequent taste preferences. From a sensory standpoint, this result may convince professional wine critics to consider temporal effects in their evaluation (apart from the natural aging process). From an economic standpoint, this result may be interpreted as the difference between a one time wine purchase (based on a given tasting) and a repeat purchase (based on the influence of taste learning). We believe that this result is actually more valuable in predicting long-term economic equilibria. If the saturation effects highlighted in this study were to be replicated across other markets (particularly the export market), they could seriously impact the supply/demand balance, with the changes in wine characteristics and consumers' preferences going in opposite directions.

Finally, we have shown how advances in enological processes, namely dealcoholization and acidification, may be accepted by consumers and may provide at least part of the solution to producers strongly impacted by climate change. However, these findings should be extended to various wine types and distinct consumption behaviors throughout the world.

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From scenarios to pathways: lessons from a foresight study on the French wine industry under climate change

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Abstract

This communication presents i) the foresight methodology carried out by the LACCAVE project on the French wine industry under climate change, ii) the main results of this two-year work (2014 and 2015) and iii) some lessons this exercise can provide to both the scientific community of "foresight studies" and the stakeholders of the French wine industry. The novelty of the method was to define adaptation strategies at the beginning of the foresight exercise, by crossing two dimensions: the intensity of innovation and the amplitude of vineyard relocation. Four pathways are presented: a "conservative" pathway that includes only changes at the margin; an "innovating" pathway that opens all the vineyards to a wide range of technical innovations; a "nomad" pathway that highlights the opportunity of vineyard relocation; and a "liberal" pathway that tests a situation where "everything is possible everywhere". We show the interest of framing the foresight exercise by predefined adaptation strategies from which pathways can be constructed. We also highlight how economic actors (i.e. wine producers) may be involved at different steps of the foresight exercise.

Keywords: wine, vineyard, foresight, climate change, France

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Introduction

The consideration of Climate Change (CC) has contributed to the renewed interest of foresight studies ("prospective" in French), exploring contrasted futures of socio-economic systems. Indeed, CC is a long-term process caused by the evolution of human activities (emission of Greenhouse Gases (GHG)) that will strongly affect the future of our society. Consequently, different future scenarios must be considered according to different economic and political decisions on both mitigation (reducing GHG emissions) and adaptation (limiting the negative effects of CC and maximizing the beneficial ones) (Hallegatte *et al.*, 2011). For this purpose, the Intergovernmental Panel on Climate Change (IPCC) has structured its work early on by referring to different scenarios, mapping a "possibility space" that stresses the importance of economic and political choices (Girod *et al.*, 2009). In a first approach, IPCC derived the analysis of climatic scenarios (and their impacts) from different contextual "socio-economic scenarios", which were built on some demographic, economic, energy and political assumptions and were responsible for different GHG emission levels. These first socio-economic scenarios were completed in the third IPCC report by storylines provided by foresight studies (IPCC, 2000, 2007). In its fifth report (IPCC, 2013), IPCC changed its methodology by starting from the elaboration of "representative GHG concentration pathways" (RCP), which then led to the development of different climate scenarios and different socio-economic scenarios (SSP). With this inversion, the definition of pathways becomes more important than the elaboration of different images of the future.

In parallel to IPCC work, an increasing number of "foresight studies" were conducted to identify impacts and challenges of CC on different sectors (health, energy, transport, agriculture, etc.), territories (country, region, city, etc.), resources (water, biodiversity, etc.) or value chains (wood, milk, cereal). These studies aim at helping policy makers or economic actors to define their strategy of adaptation to CC, taking into account that these impacts could be radically different according to each sector, territory or chain (Cairns *et al.*, 2013; Viguié *et al.*, 2014). However, some of these studies are rather "quick exercises", where a panel of experts aims to specify possible impacts of CC according to the IPCC scenarios, leading to the identification of some tendencies and adaptation leviers in the system (Aulagnier *et al.*, 2015; Schaller, 2015); others are rather "simulation exercises", where the IPCC scenarios are completed by external assumptions in order to provide inputs for modeling impacts of CC on production or land use (Fussel, 2010; Hannah *et al.*, 2013; Houet, 2015; Fraga *et al.*, 2016). In other cases a true foresight methodology (Gaudin, 2005) is developed, leading to the building of scenarios (i.e. images of the future and their related pathways) on the basis of i) a systemic and participatory approach, ii) the definition of key variables and processes of change (or driving forces) including actor strategies, iii) the selection of assumptions and coherent relations between these processes/assumptions, and iv) the narrative description of scenarios, completed or not by quantified outputs (Berkhout *et al.*, 2002; Mora *et al.*, 2014; Agrimonde, 2016).

Curiously, until 2013, no foresight study had been launched to explore the futures of the French wine industry in the context of CC. However, this industry is particularly affected by CC and must constantly anticipate its future conditions of production due to the perennial nature of the grapevine. Increasing average temperature, change in rainfall and higher climatic variability have had - and will continue to have - impacts on vine phenology, grapevine yields, wine quality and thus the evolution of the wine markets and their institutions (Ollat *et al.*, 2016). An important prospective study on the wine industry was conducted at the beginning of the XXIst century (Sebillotte *et al.*, 2003), but without clearly considering the impacts of CC. Of course, since 2003 an increasing number of studies have been conducted on wine and CC in France and in other wine countries, but they have focused more on impacts than on adaptation strategies, and few have developed a global and multidisciplinary approach (Jones and Webb, 2010; Ollat and Touzard, 2014). In this context, the members of the LACCAVE project[1] decided in 2013 to launch a foresight study on the French wine industry under CC. The aims of this study were to capitalize on the LACCAVE multidisciplinary project in order i) to provide different scenarios and pathways for the French wine industry by 2050; ii) to test a new prospective methodology focusing on adaptation pathways; and iii) to build a common vision and develop cooperative networks between researchers and stakeholders of the wine industry.

[1]Long term Adaptation to Climate Change in Viticulture and Enology. This Project is supported by INRA (meta-programme ACCAF). It involves 90 researchers from 23 teams, covering a wide range of disciplines. The project worked on all issues related to the impact of CC on the French wine production, mainly focus-ing on solutions for adaptation.

In this paper we focus on the methodology used for the foresight study, showing our attempt to build contrasted pathways for the French wine industry, by starting from a first identification of "adaptation strategies" (section 2). We then present the first results of the foresight study, focusing on the storylines of four main scenarios (section 3). Finally, we discuss about the contributions and limits of the foresight methodology and suggest recommendations which can be drawn to the actors (section 4).

Foresight methodology

1. Organization of the foresight study

The foresight exercise was conducted between 2014 and 2016 by a Coordination and Organization Unit (COU) composed by 7 members of the LACCAVE project who represented different work packages, different French wine regions and different disciplines (genetics, agronomy, climatology, economics, management, etc.). This group of researchers was completed by an expert from INAO[2] and two from the FranceAgrimer[3] department of Foresight, who brought methodological and operational support. The COU decided to follow a whole foresight approach and to adapt a previous scenario planning method to the specific issues arising from CC. The COU must thus be considered as i) the operational organization which managed the different steps of the foresight, ii) an expert panel providing controlled outputs at specific steps and iii) a reflexive group that capitalized on its own experience to improve foresight methods dedicated to CC. The COU met 12 times and combined different internal collective works (design, expertise, redaction, etc.) with consultations of other LACCAVE researchers and a survey of wine professionals from three wine regions (carried out by a master student). External communication to actors of the wine industry was also driven by the COU at different steps of the exercise.

2. The wine industry as a system

In the first step, the COU built a common representation of the French wine industry and its relations to CC. Activities and flows involved in wine production and trade may be represented as a system, which can be divided into three technical subsystems and two coordination subsystems: the "vine agrosystem" leading to the production of grapes; the "winemaking system" focusing on oenological operations; and the "value creation system" which includes all the economic actors in the value chain, including consumers. These three subsystems are framed by two others: the set of knowledge and representations constructed by actors about their activities and products; and the regulation, rules, norms and institutions orienting the wine industry. Furthermore, actors or territories may enter or leave the system.

The "vine and wine system" contributes to the emission of GHG (mainly through its logistic) and is directly or indirectly impacted by CC. This system evolves over time and can follow different pathways according to i) the nature and intensity of CC, ii) inherited structures and institutions, more or less vulnerable to CC, and iii) socio-economic (external) trends over which stakeholders in the system have little control (e.g. economic growth and affirmation of new countries in the world trade). However, the pathways will also depend on strategies developed by actors of the wine industry, orienting investment and innovation, networks and alliances, knowledge and learning process, policy and projects, etc.

3. Climate scenario and socio-economic context

To reduce the complexity of the system evolutions, one climate scenario and a set of trends in the socio-economic context have been adopted for 2050:

A "median" climate scenario has been selected from IPCC works: between 1.5 and 2°C increase in average temperature (relative to pre-industrial times) combined with an overall increase in the frequency of extreme weather events. The effects of this climate scenario vary by region, with roughly a north-south gradient:

- In the north, if maturity and productivity are often favored, the problem mainly comes from the development of new pests and pathogens, which complicates the stability of the production, both in quantity and in quality;

- In the south, drought and lack of freshness are the main handicaps, leading to high alcohol degree in wines, less and less compatible with the expectations of many consumers and public health authorities.

As far as socio-economic conditions are concerned (for the period 2017-2050), the COU assumed that i) the French vineyards will still be included in a national and European policy framework; ii) international trade and globalization will remain a fundamental movement, more or less pronounced;

[2] Institut National de l'origine et de la qualité. French national agency managing the quality labels for the French agriculture and the wine industry.

[3] FranceAgrimer is a French national agency whose mission is to implement agricultural policy, to provide information on agriculture and to improve concertation between the actors.

and iii) exceptional events were excluded such as natural catastrophe, major economic crisis or economic boom; wine remains a well identified drink, but viticultural and oenological practices will vary, as well as the organization of the wine industry, its regulations and policies, the strategies of its actors or the expectations of its consumers.

4. Construction of adaptation strategies

The novelty of the method was to define adaptation strategies at the beginning of the foresight exercise, by crossing two lines of action:

A) the choice of location of the vines may vary from staying in the areas of existing vineyards to shifting to new areas (abandonment and creation of wine regions) through relocations within or at the borders of a production area. This mobility allows finding better climatic conditions, according to altitude, longitude and type of soil;

B) technological innovation may have different intensities, from the extension of current innovations to radical innovations (biotechnology, GMO, aromatization, etc.). Technical innovations can modify the system by correcting negative impacts of CC or by taking advantage of new climatic opportunities.

Institutional changes and construction of new knowledge, which are other aspects of adaptation, were considered possibly associated with these two lines of action.

Combining these two lines of action leads to the proposal of four adaptation strategies:

- "Conservative", which integrates only incremental changes in the current vineyards;
- "Innovate to stay", which opens the vineyards to a wide range of agricultural and oenological innovations in order to maintain the current locations;
- "Nomad vineyards", which gives priority to the relocation of vineyards seeking for new climate conditions;
- "Liberal", which allows to do "everything everywhere".

5. Selection of assumptions

The COU has then collected and selected assumptions that could be linked to the development of the four adaptation strategies. The assumptions correspond to processes that may or may not occur. They were extracted from three sources:

• The outputs of previous foresight on the wine industry, mainly deriving from the 2003 INRA study (Sebillotte *et al.*, 2003). It provides a first range of processes, initially not referring to CC (e.g. *Evolution of wine consumption*), that have been systematically questioned by the COU on their possible influence on the wine system under CC;

• The expertise of 40 LACCAVE researchers, covering many scientific fields and disciplines. The researchers were asked, by E-mail and through two meetings, about the main processes they could associate with the four adaptation strategies;

• A set of 44 interviews with wine leaders, wine merchants and wine producers in three wine regions representing climate diversity (Bordeaux, Languedoc, Champagne). Each stakeholder was asked to imagine herself/himself in 2040-50 and had to tell the story that succeeded according to each "adaptation strategy" (Jouan, 2014).

From 135 assumptions, the COU finally selected 70 that were described by a statement and its opposite. For instance, the assumption WP11 is defined as follows: "*New oenological practices are developed and used to keep the current characteristics of the wines"* versus *"There are no oenological innovations that conserve the current characteristics of wine*".

6. From clusters of assumptions to four adaptation pathways

The COU has then combined the 70 assumptions in a dependent-influence matrix, following one of the structural analysis tools used in foresight studies (Gaudin, 2005). Each possible relation has been checked and collectively noted according to the influence of each assumption (+, -, +/-, " "). The matrix analysis yielded 16 clusters of assumptions, which have been analyzed (systemic analysis) and described as 16 micro-scenarios (narrative descriptions), potentially transforming the wine system.

Using a morphological approach (Godet, 2002), the COU screened the combinations between the micro-scenarios that may be relevant with the four adaptation strategies, bringing the structure of four adaptation pathways. These pathways were described by a narrative based on i) the micro-scenarios and ii) a common framework of four groups of questions:

- The general context, including the evolution of public health policy about alcohol, the orientation of public research, changes in land use policy;
- The wine international context, focusing on international definition of wine, rules of wine

labeling and origin, the European public intervention in the vineyard (plantations rights, etc.);

- The national and local context of the wine system, highlighting the relations between wine industry and research, the levels of understanding of CC impacts on vine and wine, the resilience of wine farms, consumer reaction to the evolution of wine quality;

- The direct impact on the wine system, including its governance (at the regional level in particular), the relative weight of wine regions, the evolution of economic performance (especially for export), the weight of AOP wines, etc.

Results: description of four adaptation pathways

1. Pathway to the conservative strategy

a. Facing adverse policies and increasing risks

The wine industry has failed to define clear priorities for research on adaptation to CC, facilitating the disengagement of the state from funding research on vine and wine. Data collection in vineyards is limited and the understanding of CC impacts on vine phenology, pest distribution or wine quality has not really progressed. French wine producers are facing more frequent climate risks, with one "normal" harvest in four. In this context, CC is generally perceived as a threat. Organic wine production, which requires an accumulation of observations and experiments, is not facilitated.

Water resource and fertile land are preferably dedicated to food crops, especially in the irrigated plains of the South of France where the renewal of PDO (Protected designation of origin) or PGI (Protected geographical indication) vineyards requires authorization. Wine producers who have land reserve on their farm or nearby are planting vines in more elevated or less exposed plots, with better water retention. Vineyards are strictly circumscribed to their historical areas.

b. Few innovations, new references to traditions

In this context where volume and quality tend to be more variable, wine merchants offer contracts to farmers to secure their supplies. The weakness of R&D also affects oenology. Corrective practices that could preserve the wine aromatic profile have not been developed on a large scale and dealcoholization technologies remain out of reach for many producers. Without innovation pressure, the international definition of wine and the range of authorized oenological practices remain restrictive.

At international level, the World Health Organization (WHO) strengthens its fight against alcoholic beverages by doing everything possible to limit the distribution of wines. The overall demand for wine declines, and international wine blenders remain marginal. The declining demand in importing countries maintains administrative control of plantations and a minimum level of highly eco-conditional interventions. Nevertheless, the market share of French wines remains stable, or even grows, because of the weight of PDOs, considered in part as cultural goods and less sensitive to taxes on alcoholic beverages. The vineyards producing PGI wines and wines without GI are facing significant decline.

c. Toward a restricted circle of consumers

Wine retains enough consumers that highlight hedonism and "conviviality". The concepts of "terroir", "geographical anchorage" or "traditional practices" are among the stories that these consumers love to tell. This narrative framework helps to justify the evolution of wine profiles, makes acceptable some defects caused by CC and allows individual experiments. Wines are becoming more rare, random and expensive, allowing the development of several profitable vineyards promoting traditions and singularity. In new areas available for vine cultivation, some amateurs experiment the production of new wines and some local investors explore the opportunity of replicating the traditional model existing in the traditional vineyards.

2. Pathway to the innovating strategy

a. Economic and policy context opens opportunities

The global economic context is relatively favorable to the wine industry and contributes to stabilize the French vineyards in terms of area and volume. However, WHO ban on alcoholic beverages and customs legislation aim to limit the consumption and international trade of wine. To respond to these constraints, the EU liberalizes the blending practices of "wine without GI" coming from a wider range of varieties (including GMO ones) and increases the production potential of "wholly obtained" wines in PGI areas, allowing the emergence of European brands. Private and cooperative firms improve their competitiveness on the basic and premium segments of the EU wine market, to the detriment of third countries.

In Europe, the society's expectations link the CC challenge with preservation of natural resources (water, biodiversity), environmental protection and food security. Therefore, policy choices result in a more extensive planning of agricultural land, dedicating the most fertile areas to food crops. Vine plantation is thus oriented to areas of "less agronomic fertility", in spite of a liberalization of planting rights.

b. Technological innovations for adaptation to CC

This policy encourages the maintenance of viticulture in traditional areas and their surroundings. Wine production is supported by public and private R&D working on technical innovations that address the climatic and environmental challenges. In particular, the integration of climate information, agronomic and oenological practices, and new technologies (drone and satellite imagery, predictive and optimization tools, sensors) promotes the development of "agro-climatic engineering", enabling to better take advantages of local climatic and soil conditions. Agro-climatic knowledge also enables the development of agro-ecological approaches and organic viticulture with different possible evolutions. This innovative and sustainable viticulture also benefits from new solutions for risk management, based on the integration of both new knowledge and insurance arrangements and contracts.

In wine-growing areas, conflicts between viticulture and conservation of natural resources (water, biodiversity) are limited, or even overcome: the vine requires less pesticide use thanks to the use of resistant varieties; positive contributions to the environment are recognized, in particular as natural barrier for fire whose risks increase with CC; and viticulture helps to maintain the landscape, cultural context and tourism activities.

c. Toward a new governance of the wine industry

The development of sustainable viticulture in the inherited vineyards reinforces the regional governance of the wine industry, which includes representatives of local community and civil society. New actors have also become significant in the wine value chain, such as agro-climatic and winemaking experts, or ecological and digital entrepreneurs who provide highly specialized scientific and professional knowledge. The efficient regional governance is able to set clear targets to R&D organizations, supporting dissemination and sharing of innovations in the vineyard and in the cellar. These innovations take into account upstream and downstream conditions: upstream, they preserve wine differentiation by "terroir" and organoleptic characteristics; downstream, they promote a positive perception of wine consumption in public opinion, making it compatible with health and environmental concerns. Facing increasing health concerns, R&D contributes to reduce the alcohol content, pesticides and allergens in wines. PDO and PGI wines integrate these innovations - not without difficulties - in their code of practices. By taking advantage of i) a better understanding of the links between wine, local conditions and CC, and ii) more flexibility in the definition of wine, the viticulture can extend to new, but limited, areas. Thus a new map of terroirs is emerging from the current geography, but without major upheaval.

3. Pathway to the nomad strategy

a. Globalization and societal expectations

In a more globalized world, agriculture adaptation to CC has become a major issue, but must be combined with two main societal priorities: health and environment. The WHO's work focuses on alcohol without going as far as to reduce production and exchange of wine, which is "protected" by its agricultural and cultural status. Liberalization is thus underway in the wine sector, without questioning the general definition of wine. More flexible rules on blending, origin and oenological practices (including fragmentation and reassembly of wine components) reflect this liberalization and allow the emergence of international blenders-merchants located near consumer centers.

In this context, vine planting has become totally free in the EU, especially to withstand international competition and facilitate rapid relocation of vineyards, particularly when strongly affected by CC. Despite wider requests from wine industry stakeholders, the public R&D only invests on socially acceptable topics such as reduction of inputs (including water) and alcohol.

Scientific knowledge and geo-localized information on physiological responses of vine to CC is insufficient i) to disseminate precision viticulture in all vineyards and ii) to develop new technical systems that allow efficient and sustainable wine production in the areas most impacted by CC.

b. New deal between quality and origin

The inherited concepts of "terroir", "origin", "provenance", "GIs" or "made by" remain confusing to many consumers who are still interested by a "wine from here", which is supposed to reduce risks and ensure consistency in wine quality (except in the "super premium" and "icon" market segments where consumers accept variability). This "taste of origin" is controlled by analytical characterizations. Consumer willingness to pay for defined and constant wine quality leads the producers to respond by planting vines in new areas, where new combinations between soil, climate, variety and practices can be established (promoting varieties that require low quantity of water and inputs).

- In the south, having land reserve in altitude becomes a lever for adaptation to CC (providing freshness), but the main strategy consists in planting vines in plain, where irrigation is available. PDO wines from hillsides are threatened, whereas PGI/varietal wines can find new perspectives;

- In the north, the saturation of reputed PDO areas (inducing high cost of production), as well as the increasing restrictions on pesticide use, lead investors (old or new) to establish vineyards in new climatic margins of the EU. They seek to bring further north the reputation of previous French vineyards.

c. Toward a major revision of the PDO model

These trends do not really promote organic viticulture, generally considered too risky to respond profitably to CC. Risk management becomes a key point in the wine industry (especially in the new vineyards), combining conventional individual insurance with mutual aids and contracting between producers and downstream buyers.

CC is mostly seen as a constraint by actors of the wine industry and modifies its governance, especially in the south due to the significant use of irrigation, but also in the north where societal expectations must be integrated to reduce the risk of wine image deterioration.

The relative weights of vineyards are modified and France sees the PDO wine model strongly questioned: pure "terroir wines" can no longer guarantee consistency of expectations and are evolving toward a more dynamic and flexible definition (promotion of a "way of production respecting local resources"). The French wine industry is not developing as intended in the international market, although i) its new structure of production allows to cover basic and premium segments, and ii) investors in the new north-European vineyards involve actors coming from the French wine industry.

4. Pathway to the liberal strategy

a. A more liberal context

During a first period, the vine and wine system continues to develop in a context of globalization, integration of European economies, gradual alignment of the wine market to the standards of food products, progressive consumer acceptance of technology controlled by private firms, and liberalization of agricultural and innovation policies.

In Europe, land management is more flexible and may vary according to local policies. Agriculture and wine production are free of many administrative constraints, giving more importance to i) market mechanisms and ii) firms and consumer responsibilities. Environmental and health issues are always present with impacts on the wine demand. The PDO/PGI system is weakened and evolves toward private or collective trademark, according to the country.

b. A geographical spread

Vine plantations become free, leading to a variety of spatial strategies and products:

i) Vines are planted in fertile and irrigated land where combinations of new varieties, irrigation and corrective oenology allow adapting wine to CC and market;

ii) Viticulture is leaving many traditional (non-irrigated) wine areas, including the now reputed GI vineyards. Some "spots" are still producing wine, supported by investors who seek authenticity (castles, nature) or by local groups of wine producers who manage to maintain high wine prices, in connection with tourism strategies;

iii) New vineyards are planted, mainly in northern regions (Paris Basin, Brittany, suburban areas, UK, Poland, etc.), but no new great/large wine region really emerges, because of climate risks and competition on the land.

The wine producing area maintains, then decreases, leading to a geographical fragmentation marked by diverse regional dynamics and productive poles in competition.

c. A conquering viticulture which becomes weaker

During a first period, the French viticulture remains profitable, driven by a growing international demand and the dissemination of knowledge and previous innovation, which are able to manage medium-term adaptation to CC in various climatic contexts and for different types of wine. This (initial) conquering viticulture is supported by new investors at the stages of production and trading. The power of traders increases due to their ability i) to respond to consumer willingness (taste, health, fashion), ii) to control final winemaking by more flexible oenological techniques, and iii) to manage climate risk through blending and diversified sourcing. However, the strengthened position of downstream operators, the increasing climate instability, the growing competition between "wine poles" (old and new) and the deregulation of the wine sector finally weaken many French wine producers (private and cooperative), whose collective organization decreases in most regions.

d. Wine without complex vs niches of artist wines

Some "terroir" wines are still promoted by individual strategies or financial groups investing in the luxury industry, but they become marginalized. Creative and personalized wines open new local and international niche markets by integrating innovation and/or new vine locations. They succeed even under difficult climate conditions, but are also marginal. The greater part of the wine production is marketed as "no complex wines" produced from both former PDO vineyards reconstituted around irrigated poles and new vineyards. Most of these industrial wines are blended or flavored, aiming at i) respecting environmental and health requirements, ii) following consumer demand, and iii) limiting the impacts of CC. Some sub regional brands continue to play a role in the market by referring to their historical reputations (Champagne, Bordeaux, etc.) but they are weakened. The international market is highly competitive and France finally loses market share and competitiveness.

e. Discriminant innovations with limited impacts

After a rather prosperous period, the French wine industry becomes weakened, facing i) a disorganized upstream strategy, ii) a more negative image of wine, and iii) the reduction of public support to R&D. Innovations are lacking to support long-term adaptation to CC in all the vineyards. R&D and geo-localized information on soils and grape/wine production are mainly controlled by private firms, which focus on genetics, irrigation and oenology. Private R&D investments are insufficient to upscale precision viticulture among all vineyards and to help the development of a new "terroir viticulture".

The fragmentation and weakening of many vineyards, combined with more frequent climate crises, make risk management a key issue, combining the endorsement of private insurance with contracting in supply chains and withdrawal or diversification of the vineyards.

Discussion

1. To build pathways according to adaptation strategies

In most foresight exercises the first step aims to build different images of the future at a given horizon, starting from the collection of a wide range of variables, processes and assumptions (Godet and Durance, 2011). The participants can thus project into future worlds, seen as consistent and possible. In a second step, the work consists in defining the ways, the strategies and the choices that may lead to each future scenario and could promote, influence or avoid them. This generally leads to a "strategic foresight" or "strategic planning", usually performed with the study sponsors or some stakeholders of the system.

The originality of our prospective is to have organized the work on the basis of a predefined strategic framework: four "adaptation strategies" that cross different intensities of innovation and amplitudes of relocation. Successful processes and assumptions have therefore been generated taking into account this strategic framework. Their combinations were thus selected and chained to allow the development of each adaptation strategy over thirty years. Our foresight exercise therefore does not provide images of the future, but evolutions of the system (pathways) associated with these strategies and then translated into storylines. Each adaptation strategy could be seen as a guideline around which is built each pathway. In this sense, the foresight study shows that "if the actors of the wine industry follow such adaptation strategy, the vine and wine system could evolve in such a story".

Several conditions have made this methodological option possible. First, the wine industry has a long history of adaptation to climate variability, combining innovation and choice of location (terroir). These two dimensions are the basis of many practices, rules and political negotiations (particularly in the case of PDO wines), and emerged immediately as central to cope with CC. The heuristic value of this initial choice was quickly recognized by the COU, strengthening the interest to follow this process till the end. In a more technical perspective, this choice also allowed to limit and structure the assumptions, while foresight exercises are often long and complex. We assume the risk of having excluded some original paths or some bifurcations between strategies. Nevertheless the four selected pathways are sufficiently contrasted to question the wine industry stakeholders. Ultimately, our approach joins the options selected by IPCC (IPCC, 2013), leaving aside the prior definition of socio-economic contexts at specific horizons to favor a pathway approach.

2. To involve political and professional actors at different steps

Another originality of our exercise is that wine industry stakeholders, particularly the wine producers, were involved at different steps from the production of information to the design of collective strategies.

Like most foresight studies, our approach was based on a group of experts (the COU) coordinated by several specialists in prospective studies and extended several times to a second circle of experts covering a wider range of areas (members of the LACCAVE project). We also directly involve wine producers in the first step (collection of assumptions), through original survey in three wine regions. By taking into account their reaction to the predefined adaptation strategies, we manage i) to validate the relevance of these strategies, ii) to receive comments on the approach and its aims and iii) to feed a "generator of assumptions" that could be linked to the development of these strategies in the next 30 years. The context of the COP21 promoted producers' awareness about CC, helping them to answer to our survey (Jouan, 2014). The playful nature of many face-to-face questions ("imagine you are in 2050…") also encouraged creativity. The consultation of stakeholders in CC foresight studies is common, for example using the Delphi method (De Franca Doria *et al.*, 2009) aiming at building a consensus. But here we decided to maintain the diversity of options and assumptions delivered by the consulted actors, in order to feed the debate and work of the COU.

We also decided to report to stakeholders at different steps of the foresight exercise. The presentation of our approach and the four adaptation strategies were carried out early through articles in technical journals, conferences in trade fairs, or interviews in mainstream media. However, these presentations remained very synthetic, until the final construction of pathways (Aigrain *et al.*, 2016). This communication especially helped to maintain interest and expectation on the exercise.

Indeed the work continues using the description of the four pathways as a tool to promote the construction of collective strategies of CC adaptation in wine regions. Supported by regional wine organizations and by climate KIC[4], we decided to launch "foresight forums" in contrasted wine regions, primarily in Aquitaine (November 2016). Each forum will provide i) a specification of issues and consequences of the four pathways on the regional vineyard; ii) a debate on the desired or rejected pathways and the possible levers, iii) the identification of key issues for further research and innovation development, and iv) the commitment of many actors in the co-construction of a climate strategy for regional vineyards. Each forum should bring together a panel of one hundred growers to react and interact about different pathways and questions, through suitable computing devices (tablets and real-time processing of responses). This approach is consistent with new methods of innovative design for the joint management of natural resources (Berthet *et al.*, 2016) or participatory construction of climate policy (Few *et al.*, 2007).

3. Recommendations to actors of the wine industry

The outcomes of this foresight exercise are regarded as tools to help wine producers and their professional organizations as well as research and public authorities develop their own strategies. Before the organization of "foresight forum" in different wine regions, the COU also used the knowledge generated by the two-year exercise to formulate five recommendations (Ollat *et al.*, 2016):

- Adaptation strategies strongly depend on the level of mitigation (reduction of GHG emissions) and could be reasonably implemented in all French vineyards if global warming remains below 2 °C. The maintenance of "manageable evolutions" of the French vineyards thus calls for the necessary application of the Paris COP21 agreement;

- There is no unique technical solution (such as new varieties or irrigation), no unique institutional solution (such as new insurance), but different combinations of multiple technical innovations, with spatial strategies and institutional changes. The foresight exercise leads to explore, in a systemic way, how some of these solutions could be implemented;

- These integrated solutions may be determined through a value chain approach, including the evolution of consumer preferences, which will be a key point of adaptation. This "consumer side" of adaptation emerges clearly from the four storylines describing contrasted adaptation pathways;

- These adaptation strategies should be coordinated at local and regional levels, where climate impacts are specific and the use of resources could be optimized. The foresight study has to be specified at these regional levels. This is the purpose of the "prospective forum" carried out with wine professional organizations;

- Facing many uncertainties, the best way to adapt will rely on the improvement of regional collaboration between researchers and actors of the

[4] Project « Climate Smart Agriculture Booster » funded by Climate KIC, the EU's main climate in-novation initiative.

wine industry. This is clearly another, and perhaps the main, output of such a prospective exercise.

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