

NATHALIE OLLAT AND JEAN-MARC TOUZARD, EDS

VINE, WINE AND CLIMATE CHANGE

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Nathalie Ollat
and Jean-Marc Touzard,
editors

VINE, WINE
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Preface

Climate change is a reality to which mankind must respond urgently in many sectors. However, current political initiatives on a global scale are not sufficient for a significant change to protect the climate and support sustainability. We as individuals have only limited options (but yes, we can make a contribution), and in a larger context, infrastructural, organizational and legal changes are necessary to move towards a low-carbon lifestyle to avoid continuous warming on the planet. Many initiatives to reduce carbon emissions are doomed to fail or cannot achieve the goals set as long as at the same time policies on a global scale subsidize fossil energy use with approximately USD 1 trillion per year! The questions of renewable energy use, sustainable building construction or water conservation and access to water are pertinent to the entire global population and it becomes more and more clear how dependent humans are on nature and weather (and on a longer timescale, climate).

Of all sectors that need to implement changes, agriculture is one of the most important ones because it is the basis for food production. Climate is a decisive factor for the cultivation of agricultural crops, from the geographical suitability to the effects on yield and quality. Throughout human history, these strong ties determined the cultural and economic development of regions, created local identities and have influenced migration and settlements. In the field of agriculture, these connections have their most intense expressions in the production of grapes and wine. Grapevines have been cultivated for several thousand years and during this long history specific growing regions were established, whose climatic conditions played a decisive role in the formation of specific wine characteristics from certain varieties. Over time, climate parameters (such as temperature) were used to delimit the boundaries of wine regions and to develop legal frameworks that are still present in the current definition of wine regions throughout the European Union for example. The "European experience" has been used as a model, in that climatic indices of different European wine regions were applied to non-European regions to determine general suitability and the choice of cultivars.

In the context of climate change, agriculture and therefore also viticulture are also contributing to greenhouse gas emissions and environmental pollution through cultivation practices but there is a potential for mitigation because soils can have substantial carbon storage capacities. At the same time it is also important to recognize that the grape and wine industry needs to reduce its environmental footprint well beyond mere field cultivation practices, including processing, packaging, logistics and many more areas.

The French grape and wine industry is unique among all global wine industries because of its economic value, the social impact, the tight regulations, the diversity of meso-climatical (regional) conditions, its terroir-based production idea, regional specifications with respect to varietal use, cultural methods and product type conferring regional and local identities with a long history. Preserving this closely intertwined system in a changing climate under rapidly changing environmental, social and economic conditions is an enormous challenge. Contrary to previously managed crises such as phylloxera or the introduction of fungal diseases (powdery and downy mildew), where causal agents could be relatively fast identified and responded to, the current challenge (i.e. climate change) is global, occurs relatively slow (timescale of decades or longer), is for many not immediately evident (despite more and more signs of acceleration) and will develop most of its impact in the "distant uncertain" future. This makes it the more challenging to convince the entire industry including all stakeholders and the consumers, that an immediate reaction is required. And reacting now is of larger importance for the grape and wine industry than for other agricultural sectors because of the longevity of plantations, thus largely defining a product for 2050–2070 and may be beyond, by planting now.

Adaptation has such a regional, varied, social and economic diversity, as well as an array of institutional and regulatory (thus political) facets which need to be addressed to devise something like a national strategy including all stakeholders which comprises to some extent even the general public (like in grape-producing areas).

The current compilation from the LACCAVE initiative (it is more than a project) with different climatic analyses, definitions of regional environmental limitations and characterization of specific regional conditions, plant genetic, physiological and cultural systems adaptation studies, identification of disease threats, oenological responses to the observed and expected changes, consumer expectations, perceived socioeconomic consequences in different regions and the formulation of adaptation measures on different levels in the regional production chains including members of the industry and around is as unique as the French viti-vinicultural system.

This collection of initiatives around one large topic is special because it includes bidirectional knowledge transfer from science to the industry and back, which is very important to secure acceptance of results. LACCAVE is a unique and very comprehensive "pilot study" and in many ways can become a role model for grape- and wine-producing areas around the world in the methodological array of tools used, from climate and physiological models (natural sciences) to behavioural models and "Climathons" (socio-economic sciences) to educational concepts. It is an example for how science in all dimensions can act together with authorities (local, regional, national), industry members and local populations to come up with a coherent plan for the future. And of course, the process is not finished yet.

System transformation to form the basis of resilience of an entire industry towards future environmental conditions is a task which needs to include all the facets of human anxiety and innovation. "Will viticultural areas have to move outside of their current boundaries (nomads)?", "should we change anything at all (being conservative)?", "let's be innovative", to "liberate the system completely (which would be equal to destroying the current "French connective system"). LACCAVE succeeded to devise a common strategy in a "democratic" system.

The goal is not to adapt and survive for a certain time with a traditional product for a certain price. The goal is to show ways for a long-term survival including concepts such as “agroecology”, soil conservation, disease tolerant varieties, innovative water and energy management, etc. and, most importantly, implement the outlined strategies and solutions into educational formats at all levels. Because if we are not able to plant the need to change and the necessary tools to achieve change in the heads of the next generations, we will not succeed in managing the climate crises.

Hans Reiner Schultz,
President, Hochschule Geisenheim University (Germany)

General introduction

Nathalie Ollat and Jean-Marc Touzard

Climate change is a reality that impacts all of us and is changing our way of life on Earth. The findings of each successive IPCC[1] assessment report – the most recent being the sixth – are becoming increasingly alarming, hence the need to act with the utmost urgency (IPCC, 2023). Agriculture is on the front line, both as a major emitter of greenhouse gases and an industry highly impacted by its dependence on the climate. These links to the climate are of vital importance to the French viticulture and wine industry. Historically, they are in integral part of the concept of terroir and play an important role in the location of vineyards, the choice of grape varieties and practices, the definition of wine qualities, and the organization of wine markets (Dion, 1990). Climate change is upsetting a delicate balance that has developed over time and is part of the very foundations of an activity that has such a special place in the French economy and society (Ollat *et al.*, 2020, 2021). This poses a major challenge for everyone involved in the industry, from winegrowers to wine consumers, not to mention the researchers who produce knowledge about its various components.

The heatwave that hit France in 2003 brought home the challenges posed by climate change, leading researchers to begin looking into it the following year (Ollat *et al.*, 2020), with stakeholders in the viticulture and wine industry either supporting their research efforts or taking action themselves to assess their carbon impact. Meanwhile, wider scientific and political discussions at international conferences such as the Conferences of the Parties (COP) quickly established that measures to reduce greenhouse gas emissions would not be enough to curb climate change and that adaptation was becoming a key issue for agriculture and the food industry (Soussana, 2013). In 2011, for example, the French National Institute for Agricultural Research (now INRAE) set up a multidisciplinary framework called the Adaptation to Climate Change in Agriculture and Forestry (ACCAF) Metaprogramme to support projects looking into climate-change adaptation in agriculture and forestry (Caquet, 2017). Scientists involved in viticulture and wine, some of whom were already working on climate change projects, took the opportunity to put forward a project entitled LACCAVE: *Long-Term Impacts and Adaptation to Climate Change for Viticulture and Enology*. The main aim was to pull together all relevant research being conducted in France and to make the results more readily available to industry stakeholders (Ollat and Touzard, 2014). Published after 10 years of activity (and two IPCC reports), this book takes stock of the work conducted to date, offers a state of knowledge on the subject and reports on the approaches that have moved industry

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[1] Intergovernmental Panel on Climate Change, a body that advances knowledge on climate change.

stakeholders to action. It aims to appeal to a large number of readers, in keeping with the spirit of participation that has driven LACCAVE since its inception. It is divided into two main parts. The first comprises nine chapters describing the impacts of climate change on grapevine, soil and wine quality, followed by technical and geographical adaptation levers: the development and selection of new varieties, vine management, water management, oenological solutions and reference to climate variability in a given area for vineyard reorganization. The second part is made up of seven chapters that explore how industry stakeholders work with researchers and use the levers available to develop knowledge and strategies: the perception of impacts among winegrowers and consumers and the role of professional organizations, research, training and participatory approaches leading to the emergence of solutions at local level, the design of new winegrowing systems, and the creation of a national adaptation strategy. The two parts put forward a wide range of scientific contributions, with particular attention paid to the methods employed. Each chapter features in-depth details on experiments, systems, results and actions in special text boxes.

Changing climate a cause for concern

Since the advent of the twentieth century, the atmospheric concentration of CO_2 has risen by 40% (reaching 419 ppm in 2023), with almost half of this increase occurring in the last 30 years. As a result, air temperatures in France have increased by an average of nearly 1.8°C year on year, a process that has gathered pace since the 1980s, with every year since 1990 being warmer than the average since 1900, and the warmest years being 2014, 2018, 2020, 2022 and 2023 (Météo-France, 2024, figure Intro-1A). This in turn has led to an increase in soil temperatures up to a depth of 50 cm (Schultz, 2022). However, annual rainfall has shown little change, increasing slightly in the north of France and falling in the south, with more significant decreases depending on the season and region. In the Mediterranean region, the number of cycles in which winter precipitation (when soil water is recharged) fell below 200 mm increased during the period 1990–2021 (table Intro-1). Furthermore, an increase in potential evapotranspiration brought about by rising temperatures has been recorded at vineyards located at various latitudes across Europe (from Avignon to Geisenheim in Germany), although this is not a systematic occurrence (Schultz, 2017).

Compared to the 1976–2005 period, warming is set to continue without any significant difference between the various emissions scenarios that may play out between now and 2050 (+1°C to 1.5°C). In the most pessimistic scenario, temperatures in south-eastern France could rise by more than 5°C by the end of the twenty-first century, with a spectacular increase in the number of heatwave days (Corre *et al.*, 2021; figure Intro-1B and figure Intro-2). Precipitation trends cannot be predicted with any great certainty (Zito, 2021; Ollat *et al.*, 2021). Nevertheless, longer droughts are expected in the years ahead, particularly in southern and western France (Corre *et al.*, 2021). Some Europe-wide simulations point to a 10%–30% increase in actual evapotranspiration as early as 2050, with a water balance (rainfall minus potential evapotranspiration [PET]) that could fall by as much as 120 mm in southern regions (Cardell *et al.*, 2019). These projections are confirmed by the work of Zito *et al.* (2023), which provides the most recent simulations of climate and bioclimatic indicators for 21 French winegrowing regions on an 8×8 km grid. Any rise in temperature

Table Intro-1. Median winter (October to March) precipitation values over the historical period at French winegrowing sites and differences between the period before 1990 and the last 30 years. According to N. Saurin, AgroClim-INRAE data.

	Start of the series	Median […–1989] Recharge (mm)	Median [1990–2021] Recharge (mm)	Difference between [1990–2021] and […–1989] Recharge
Marseillan-Plage	1956	349.4	292.5	**–56.9**
Gruissan	1962	403.6	319.9	**–83.8**
Colmar	1973	213.2	233.3	20.1
Mauguio	1956	415.2	320.0	**–95.2**
Montreuil-Bellay	1977	334.8	308.5	–26.3
Fagnières	1971	312.3	295.1	–17.2
Avignon	1968	362.2	354.0	–8.2
Villenave-d'Ornon	1961	518.7	504.8	–14.0

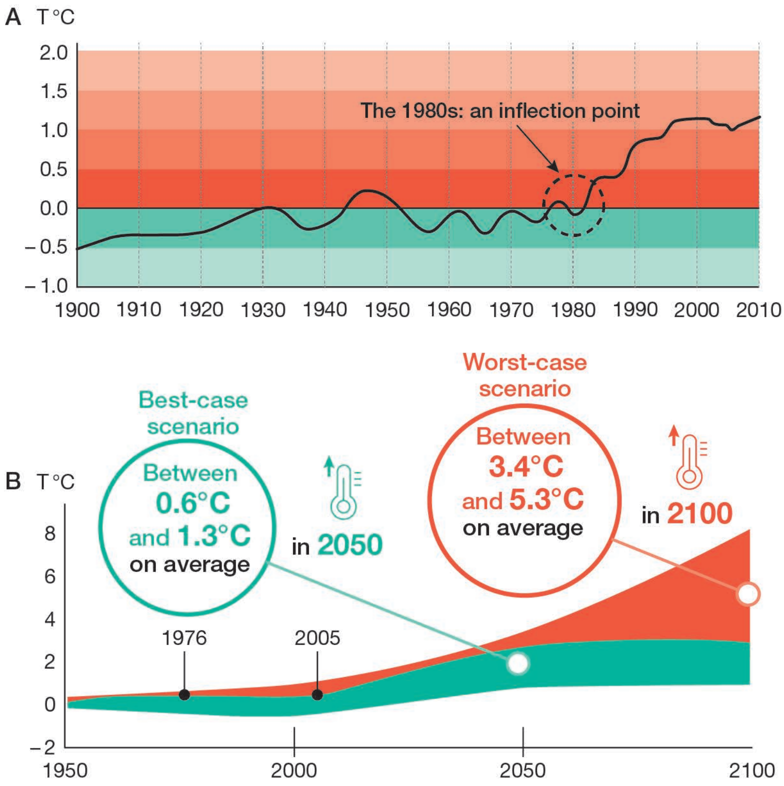

Figure Intro-1. Variations of average air temperature in France since 1900 (A) and simulated figures for the twenty-first century (B). The temperature has risen by almost 1.8°C over the last century and will continue to rise at a variable rate depending on greenhouse gas emissions scenarios. Increases are expressed in relation to the reference period (1976–2005).

also increases the frequency and intensity of extreme events such as storms and heatwaves, with impacts including the increased risk of fire, the destruction of infrastructure and ecosystems, and negative effects on human health (IPCC, 2023). These last few years are a perfect illustration of the gravity of the situation, both in France and globally.

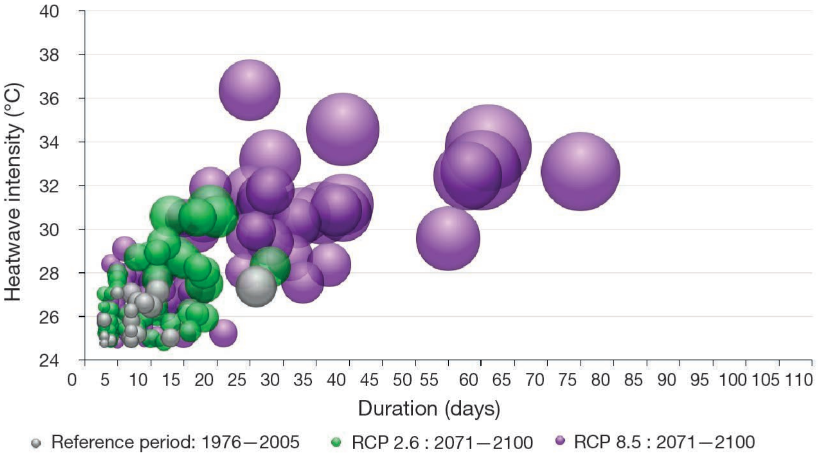

Figure Intro-2. Observed (1947–2018) and simulated (through to 2100) annual heatwave characteristics for different scenarios and time frames. Source: Météo-France.

The consequences in store for viticulture and wine – which have been noticeable since the 1980s – are a cause of great concern to industry stakeholders: harvests occurring up to 20 to 30 days earlier by the end of the twenty-first century (Zito *et al.*, 2023); a possible increase in the risk of spring frosts (Sgubin *et al.*, 2018; Bois *et al.*, 2023); temperature increases during grape ripening, affecting their winemaking potential (Van Leeuwen and Destrac-Irvine, 2017; Van Leeuwen *et al.*, 2022a); changes in the risks associated with diseases and pests, although these remain difficult to predict (Caubel *et al.*, 2014; Bois *et al.*, 2017; Zito, 2021); more frequent and more intense droughts, with an impact on yields (Lebon and García de Cortázar-Atauri, 2014). The current situation and forecasts are concerning for all traditional winegrowing regions, where winegrowers fear for their ability to retain markets and ensure their continuing financial sustainability. In some winegrowing areas, however, these new climate conditions could have less of a negative effect, such as in Alsace (Duchêne and Schneider, 2005) and the Loire Valley (Touzard *et al.*, 2020), at least until 2050. Furthermore, some regions not especially known for winegrowing at this moment in time are showing potential (Ollat *et al.*, 2016b), among them Brittany (Zavlyanova *et al.*, 2023), raising the prospect of a “new viticulture geography” by the end of the century.

The LACCAVE project: a systemic and participatory approach to adaptation

When it comes to exploring the issue of climate change adaptation, the specific characteristics of the viticulture and wine industry make it a unique and interesting subject for scientific research. The importance of wine production to the French economy is the backdrop to that. The industry employs many people directly and indirectly and accounts for a significant chunk of French exports (nearly €15 billion worth in 2022). There is also a cultural side to its status, given its effects on tourism and France's appeal as a destination. The industry is also very well organized and regulated by the system of protected designations of origin and geographical indications, which provides a legal framework encompassing the location of vineyards, winegrowing technologies and practices, and wine quality and markets. The fact that environmental, technical, economic and political factors are closely interlinked means that innovations and the changes needed to adapt to them require an interdisciplinary approach as well as discussions to bring the issues of priorities and coordination within the industry more sharply into focus. The scale of long-term investment, ranging from the vineyard to intangible assets such as a wine's reputation, is so significant that stakeholders need to look several decades ahead into what the future of climate change might hold. Planting a vineyard today involves acquiring the knowledge needed to envisage the wine it could produce in 2050. All these issues combine to make this high added-value industry a model for a pluridisciplinary approach to the analysis of climate change adaptation (Ollat *et al.*, 2020).

LACCAVE brought together a scientific network of 22 laboratories affiliated with INRAE, France's National Centre for Scientific Research (CNRS), and the universities and *grandes écoles* located in the country's main winegrowing regions and covering an array of scientific disciplines – from climatology and social sciences to genetics, physiology, agronomy, oenology and pathology. The network also forged ties with FranceAgriMer, the French National Institute of Origin and Quality (INAO), the French Wine and Vine Institute (IFV), engineers from the country's chambers of agriculture, and representatives of France's main wine trade associations.

The project's scientific objectives were to explore the long-term impacts of climate change (2050) on grapevine cultivation and wine production at a regional level and to acquire knowledge for developing and evaluating adaptation innovations and strategies for these winegrowing areas. In line with the ACCAF metaprogramme priorities, the objectives were also to provide a structure for French research into these issues and make it more visible, the idea being to better respond to demand from industry stakeholders and, in a broader sense, to disseminate knowledge and thereby raise climate change awareness among these stakeholders and society in general.

Over 10 years, LACCAVE met these academic, organizational, expertise-related and developmental challenges thanks to a wide range of initiatives and outcomes. This positive dynamic was made possible by the very duration of the project. Targeted studies into different aspects of adaptation, from planting material to analysis of consumer behaviour, were conducted over a sufficiently long period for a perennial crop and, ultimately, for industry stakeholders to take note of the climate issue. Other more methodological studies have yielded indicators, tools and models for enhancing simulations at a local level, assessing risks and mapping out adaptation. Internal think-tank seminars have led to more systemic thinking on key issues relating to adaptation, such as water and soil management. Participatory approaches have been rolled out gradually to help identify solutions at a local level, co-create more resilient systems, and conduct a foresight study leading to the development of a national industry-adaptation strategy. Finally, the project also included science events open to industry stakeholders – such as trade fairs – and to the international scientific community, namely with the organization of two international conferences and the development of several European projects.

In mapping out the adaptation process, LACCAVE focused mostly on 2050, by which time the projected temperature increases would be no more than 2°C higher than the reference period (1976–2005), even though several local-level climate simulations have also been conducted for the end of the twenty-first century (Neethling, 2016; de Rességuier *et al.*, 2020; Zito, 2021; Zavlyanova *et al.*, 2023; Zito *et al.*, 2023). It is with this timeline in mind that the project's participants worked together to create a shared vision, an analytical framework and methods that will bring about the requisite interdisciplinary approach to respond to the need for adaptation knowledge. They soon agreed that climate change is an ongoing and multidimensional process, that a great deal of uncertainty surrounds the forms it will take in the future, which vary at local level, that its impacts are global (not least on resources and ecosystems), and that adaptation must be viewed broadly, including biological processes driven by human action in a number of fields and scales (Viguié *et al.*, 2014).

The LACCAVE community thus adopted a common definition of adaptation, which is regarded as all the processes and actions that a society, region or industry implements to modify its activities in response to observed or expected climate changes, thereby minimizing the negative effects of this change and maximizing its beneficial effects (Hallegate *et al.*, 2011; IPCC, 2014; Caquet, 2017). As such, adaptation must be systemic and involve the analysis of impacts, vulnerability and risks on various spatial and temporal scales, by combining technical levers (Barbeau *et al.*, 2014), and also giving thought to the location of vineyards, rethinking business strategies and considering the growth of the industry through its markets, institutions, regulations and the development of technical and scientific knowledge (Viguié *et al.*, 2014; figure Intro-3). It was clear from the outset that there would be no single solution, such as a technological fix, and that different levers would have to be pulled together as part of strategies that could be overseen within a "sectoral system of innovation and adaptation" (Boyer and Touzard, 2021).

In general terms, LACCAVE favoured anticipation as a means of adaptation rather than reaction to the proven effects of climate change (Viguié *et al.*, 2014). The project also highlighted the importance of risk perception and the conditions of acceptance of change by stakeholders in the value chain (from producer to consumer), which are crucial to getting them to commit to adaptive strategies (Teil, 2017; Neethling, 2016; Boyer and Touzard, 2021). These issues are dealt with in chapters II-1 and II-2 of this book. The scale of the changes needed for adaptation has also been considered: incremental changes, such as modifying cultivation or winemaking practices, can no doubt enhance the short-term resilience of winegrowing businesses, but implementing them one after another may not suffice and could hinder long-term adaptation (Viguié *et al.*, 2014; Caquet, 2017). In the short term, there is unquestionably a need to consider no-regrets measures, namely those that are worthwhile regardless of the extent of climate change. Agroecology and agronomic practices preventing erosion fall into this category. The flexibility and reversibility of resources committed to adaptation should also be factored in, such as by diversifying grape varieties or making institutional changes, as opposed to investing in costly technological solutions that risk locking in technical systems (Viguié *et al.*, 2014). Such is the importance of the long term for a perennial crop and the intensity of the climate change predicted for the second half of the twenty-first century that adaptation should be seen as a continuous, systemic and transformational process, which may involve radical changes such as a general renewal of grape varieties or a major relocation of French vineyards (Caquet, 2017; figure Intro-4). Given the intensity and speed of climate change, these potential responses should be

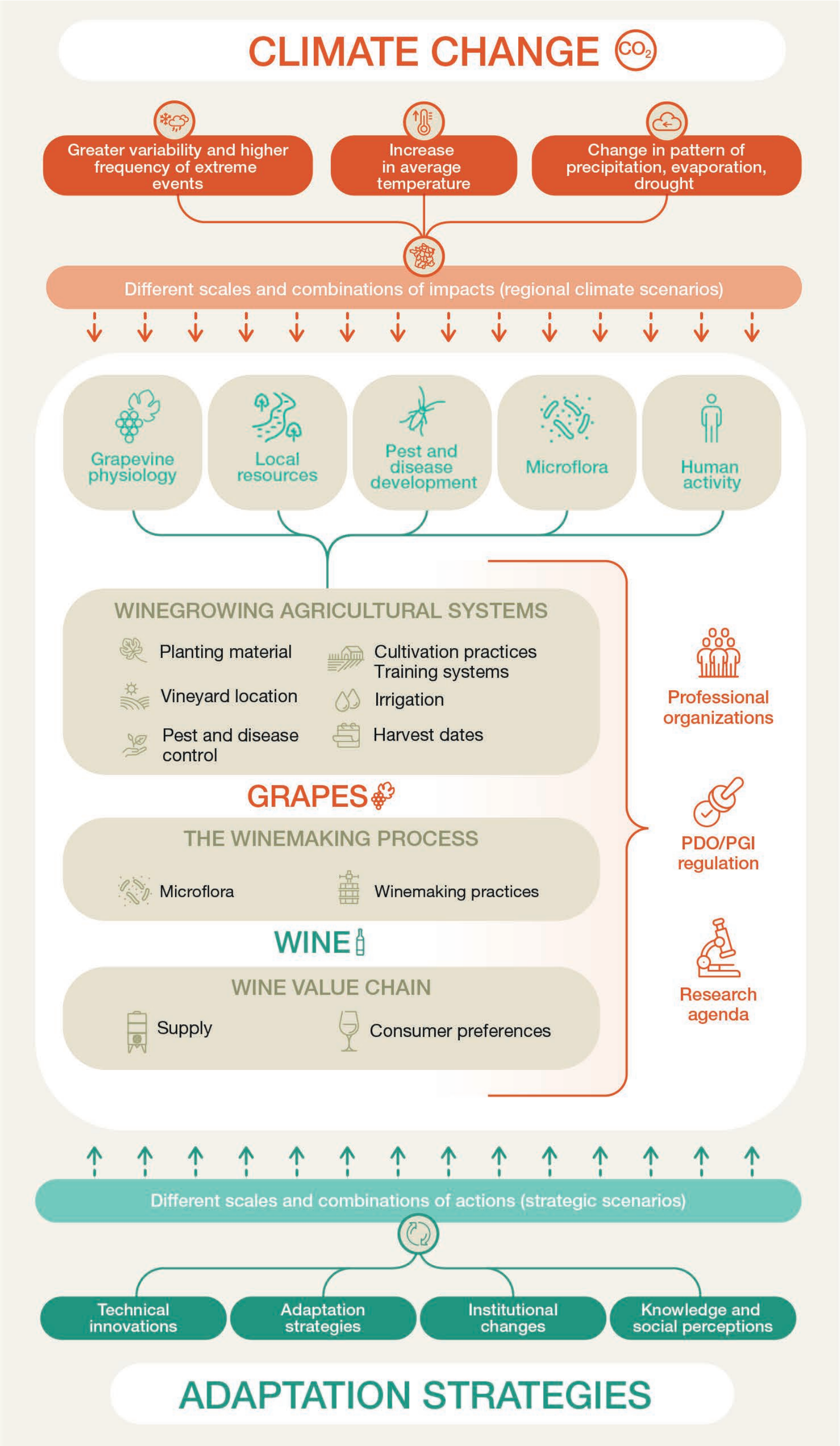

Figure Intro-3. Systemic approach to adapting to climate change in the viticulture and wine industry, according to LACCAVE. Source: Ollat and Touzard (2014).

explored and tested. As part of these processes and to encourage anticipation, it is vital that stakeholders, including scientists, interact and share experiences with each other. Participatory research is proving crucial to the production of scientific knowledge that spurs action in a context typified by urgency and uncertainty and where a host of levers need to be considered if we are to adapt. These participatory approaches were trialled on various occasions and on various scales as part of LACCAVE, and will be covered in detail in the second part of this book (chapters II-5, II-6 and II-7).

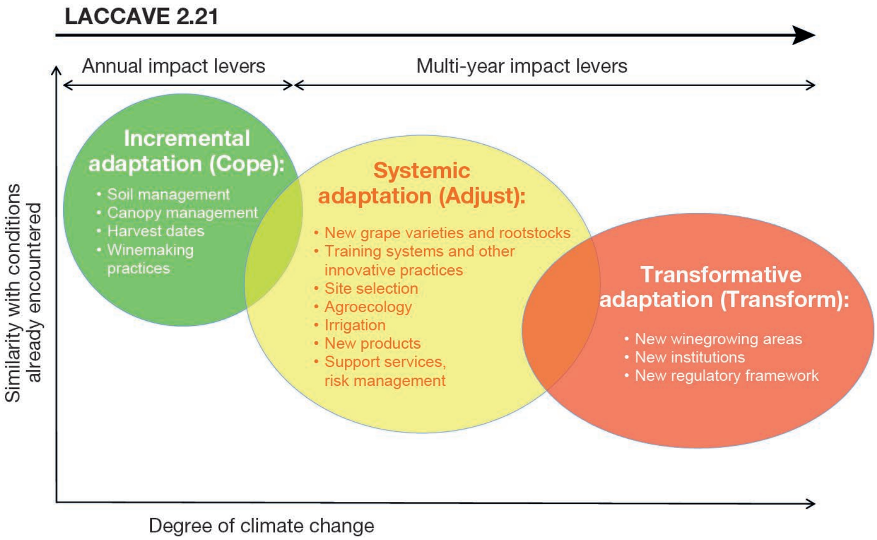

Figure Intro-4. Diagram showing adaptation processes in accordance with past experience of climate conditions and the intensity of climate change. Adapted to the viticulture system based on Thornton (2014).

This vision of adaptation formed the analytical framework of the LACCAVE project and the basis of the foresight study "The viticulture and wine industry and climate change through to 2050" (Aigrain *et al.*, 2016c), which is the subject of chapter II-7 of this book. Though a key issue, mitigation was not studied as part of the project and will not be discussed in much depth in this book. It will be covered in the conclusion as something that is likely to become a prerequisite for adaptation.

Key results of the LACCAVE project

The range of approaches implemented through the LACCAVE project yielded some key results, which are summarized below and will be expanded on in the book.

The development of shared expertise

Significant effort was made throughout the LACCAVE project to summarize the main impacts of climate change and the levers for adaptation, a process that involved leading academic and industry publications (Ollat and Touzard, 2014; Quénol, 2014; Ollat *et al.*, 2017; Ollat and Touzard, 2018; Van Leeuwen *et al.*, 2019a; Naulleau *et al.*, 2021). While these studies focus on a specific area of impact or adaptation, they generally form part of a pluridisciplinary approach that puts them into context and provides a better understanding of the contribution they can make. Pluridisciplinary contributions were made on issues vital to climate change adaptation, such as water management, biotic interactions, soils, the determination of ideotypes for grape varieties, regional approaches to viticulture, data management, the coordination of value chains, and research into the wines of the future. These adaptation-related areas of action each involve interactions between ecosystems, technical levers, socioeconomic relations and organizations, and knowledge. These areas are building blocks for more global adaptation strategies, some of which are included in the national industry strategy. Participatory seminars have been held on these themes, with presentations made available on the project website[2] and summaries that provided material for the first part of this book.

Anticipation: modelling and forecasting

Modelling is central to the sciences of anticipation and adaptation. LACCAVE contributed to the development of these approaches, making simulated agro- or ecoclimatic indicators for future climate conditions available, and to the spatial assessment of potential climate risks and opportunities for French vineyards. As well as producing purely climate-related data, the intention is also to link those data to grapevine physiological models such as phenology or, in the longer term, crop models (García de Cortázar-Atauri, 2006; Quénol *et al.*, 2017; García de Cortázar-Atauri *et al.*, 2017; Sgubin *et al.*, 2018 and 2022; de Rességuier *et al.*, 2020). Models have been used at vineyard level in the Languedoc region to help local winegrowers to create cropping systems that are resilient to climate change. These systems are tested using in silico climate simulations offering the option of dealing with water management problems and heat risks (Naulleau *et al.*, 2022a and 2022b). These approaches and the use of modelling for vineyard adaptation are described in chapters 1 and 9 of part one of the book and in chapter 6 of part two.

Foresight studies are also part of the science of anticipation. One of the key outcomes of the LACCAVE project was a foresight study conducted between 2014 and 2019 by a group of scientists in partnership with FranceAgriMer and INAO, and with the active participation of Montpellier SupAgro. As a tool for developing scientific pluridisciplinarity within the project and for spurring industry stakeholders in the main winegrowing regions into action, this foresight study helped national industry organizations draw up an adaptation strategy, which was presented to the Minister of Agriculture in 2021. This foresight study approach is presented in full in the final chapter of this book.

Participatory approaches

LACCAVE invested heavily in participatory approaches with a view to encouraging and supporting viticulture and wine industry stakeholders in the development of adaptation solutions and strategies at different scales. Aside from their contributions to the surveys detailed in chapter II-1, these stakeholders were regularly invited to take part in project seminars and discuss their expectations, the actions they were taking and their vision of adaptation (Ollat and Touzard, 2014). As part of the aforementioned foresight study (and chapter II-7), forums attended by over 500 people were held in seven regions to identify adaptation scenarios for vineyards there and to put forward solutions. The data collected were used by industry leaders to draw up the national strategy with the

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[2] https://laccave.hub.inrae.fr/.

support of the LACCAVE foresight study team (Ollat *et al.*, 2020). Stakeholder participation, combined with modelling and a participatory approach (which will be presented in chapter II-6), is also central to the co-creation of management systems that are resilient to climate change. Other original participatory approaches, such as viticulture Climathons, were adopted and encouraged a range of local stakeholders to come up with vineyard adaptation solutions (chapter II-5). Efforts were also made to identify existing and potential initiatives and innovations and to publicize them more widely and, if necessary, give people access to the knowledge produced and pooled in the LACCAVE network. The Vineas platform, which brings this information together, is another example of this participatory approach, albeit online (box II-5-5).

Training: front and centre in the LACCAVE project

Finally, LACCAVE was firmly committed to training. Ten doctoral candidates carried out their research as part of the project or were closely associated with it. Three of their theses dealt with the genetics and physiology of adaptation (Coupel-Ledru, 2015; Rossdeutsch, 2015; Duchêne, 2015), while five addressed local-level pluridisciplinary adaptation, often integrating modelling approaches (Neethling, 2016; Delay, 2015; Le Roux, 2017; Naulleau, 2021; Zito, 2021), and the remaining two economic issues (Boyer, 2016a; Fuentes Espinoza, 2016). Around 20 Master's students from a range of programmes also worked on the project and contributed to its success. They deserve the utmost credit for this, and they also helped to write the book's various chapters and text box features. The knowledge produced through the LACCAVE project has also been seamlessly integrated into viticulture and wine training modules. Several of these modules were entirely created by teachers involved in the project, helping to raise awareness of climate issues in university and engineering school courses. Thanks to the work carried out through the LACCAVE project, improvements have also been made to other more technical training courses for industry stakeholders, for example at the initiative of the IFV and French chambers of agriculture (box II-4-2). Examples of these courses can be found in chapter II-4.

Conclusion

Over a period of 10 years, the LACCAVE project led to the creation and organization of a network of researchers who came together to produce knowledge and tools to help the French viticulture and wine industry adapt to climate change and support industry stakeholders with their strategic thinking. Gaining a better understanding of the impacts, exploring levers for adaptation and co-creating strategies at different scales has posed challenges from a research standpoint. Yet though the scientific and political stakes have been high, these challenges have been especially stimulating. The LACCAVE scientific community rose to them by taking a pluridisciplinary approach focused on action and the dissemination of its findings across society. It learned at least as much from its interactions with industry stakeholders as from the development of more traditional scientific methods combining observation, surveys modelling and analysis. Though there is still much to be done, the primary aim of the LACCAVE project was to build up knowledge with a view to promoting adaptation actions within the industry. We can say in all modesty that it succeeded in doing that, as the 16 chapters of this book demonstrate.

PART 1

From impact studies to adaptation levers

CHAPTER 1

USING INDICATORS AND MODELS TO STUDY THE IMPACT OF CLIMATE CHANGE ON GRAPEVINE

Iñaki García de Cortázar-Atauri, Marie Launay and Renan Le Roux

Introduction

Since the first studies on the impact of climate change on agriculture were published in the late 1990s, researchers have used various tools. In addition to experimentation, which will not be covered in this chapter, two tools have become widespread: climate indicators and models.

Viticulture was likely one of the first agricultural systems to be studied to characterize the impact of climate change on this type of production on vineyards across the globe. Many French and international research teams have focused on the impact of climate change on viticulture, with early modelling work done by Bindi *et al.* (2000a and b). Several thousand research projects have been conducted to date to characterize the impacts[3] of climate change on viticulture across different scales, from biological processes (i.e. development) to the spatial distribution of vineyards (from local to global).

Characterizing the climate of viticultural regions is vital for local producers, managers, plant breeders and decision makers. This information can be used to develop and implement adaptation strategies to improve, maintain or establish viticulture in each region under a changing climate (Caubel *et al.*, 2015).

In this chapter, we present a historical overview of the main research carried out in recent years to characterize the impact of climate change on winegrowing areas. We provide several examples and offer advice on how to use climate indicators and models. Finally, we introduce several avenues for future research.

Historical context for the development of models and indicators applied to climate impact studies

This section reviews what is known about the two main methods that have been used to study the effect of climate change on viticulture: indicators and models.

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[3] In September 2024, more than 4,030 articles were referenced in Google Scholar.

Climate indicators

Climate indicators are based on climate variables (temperature, rainfall, wind, etc.), which provide summary information (for example, the number of frost days) about the climate in a given location. Indicators were quickly applied to viticulture to characterize different winegrowing regions (as in Winkler [1962], where the sum of the mean temperature above 10°C between April and October was used to classify climate regions in California) or grape variety distribution (as in Huglin [1978], who developed the heat sum index, which accounts for mean and maximum temperatures and latitude to classify winegrowing regions associated with certain grape varieties). In the early 2000s, Tonietto and Carbonneau (2004) used several indicators (Huglin's heat sum index, the cool night index and Riou's drought index [1994]) to develop the first multicriteria climate classification for vineyards on a global scale. This research was probably among the last to consider vineyard climate as stationary.

After the 2003 heatwave, Seguin and García de Cortázar-Atauri (2005) showed changes observed in viticulture in France and, using Huglin's heat sum index, explored how heat conditions could change between 2005 and the end of the century. Around the same time, Jones *et al.* (2005) proposed a classification of grape varieties based on the average temperature during the growing season (April–October in the northern hemisphere, October–April in the southern hemisphere) within the regions where each grape variety has historically been grown. This work was the first to show that grape varieties can have a degree of plasticity, although this has yet to be precisely quantified. In 2006, White *et al.* published the first study on the impact of climate change on vineyards in the United States. Their findings, based exclusively on temperature indicators, predicted a decline of up to 81% in the winegrape production area.

It was not until the early 2010s that the first indicator-based studies on the impact of climate change on viticulture were carried out at the European level. This research includes studies by Santos *et al.* (2012) and Moriondo *et al.* (2013), who described the changes already observed in European vineyards and used these data to predict future changes. They found that significant changes had occurred in winegrowing regions. Moreover, they predicted that climate change would lead to more favourable weather conditions in northern vineyards (Champagne and Alsace in France) and increasingly difficult conditions in southern regions (mainly due to high temperatures and drought). However, the intensity of these predicted changes was highly dependent on the greenhouse gas emission scenario. Hannah *et al.* (2013) used a set of monthly indicators to determine global viticultural suitability in 2050. They described a decrease of the suitable land area compared to the current surface area ranging from 25% to 73% depending on the region. Meanwhile, Van Leeuwen *et al.* (2013) identified limitations of climate indicators, which make it difficult to incorporate potential adaptations that could limit the impact of climate change on viticulture.

In 2019, Santillán *et al.* analysed the impacts of climate change on vineyards around the world based on agroclimatic indicators to assess the adaptation needs of each winegrowing region. Finally, the Australian wine industry produced an exhaustive atlas of the impacts of climate change on all the country's vineyards, describing indicators that account for changes in temperature and rainfall (Remenyi *et al.*, 2019).[4]

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[4] https://www.wineaustralia.com/growing-making/environment-and-climate/climate-atlas.

However, all these studies used empirical approaches that are unable to comprehensively integrate the mechanisms by which climate change impacts plant function (for example, the effect of temperature on plant phenology, growth and hydraulics). Moreover, climate indicators have their limitations when it comes to extracting knowledge that can be used to create adaptation strategies.

Models describing grapevine development

Mathematical models can be divided into two main categories: statistical models, which do not consider a system's internal processes, and mechanistic models, which describe and quantify each process within a system (García de Cortázar-Atauri, 2006). Several types of models have been developed to study agricultural processes: models that focus on processes; models that describe plant organ development, architecture and function; models that predict variables of interest (yield, quality) based on interactions of varying complexity with explanatory variables (e.g. water status or climate); crop models that consider the interactions between different system components (plant × soil × climate × crop management sequence); models that integrate the landscape and biotic factors such as diseases; and finally, models that describe farmers' decisions (multi-agent models). These models provide a conceptual framework for studying and exploring the behaviour of different systems in silico. Without going into an exhaustive description, many studies have used different types of models to characterize the impact of climate change on grapevine at different scales.

Bindi *et al.* (2000a and b) were the first to perform crop modelling on viticulture in Europe (specifically in Tuscany, Italy). In 2006, García de Cortázar-Atauri adapted the STICS crop model[5] (Brisson *et al.*, 2009) to grapevine and carried out the first study on the impact of climate change on French vineyards for the 2070–2100 period. As part of this research, several adaptation strategies were explored. Webb (2007) carried out similar work around the same time on Australian vineyards using the VineLOGIC model.

In 2010, the findings of the ANR[6] CLIMATOR project (Brisson and Levrault, 2010), which studied the impact of climate change on French agriculture (including viticulture), were presented. This groundbreaking research compared the results of several models for each cultural system and described the main impacts in France. They predicted phenological advance, greater water stress, and production disparities between vineyards in the south (decrease) and those in the north (increase). Subsequent work was carried out using these same crop models to explore impacts at different scales and investigate different issues such as changes in water requirements for grapevine irrigation (Fraga *et al.*, 2018). In addition to these studies, an analysis of crop models adapted to grapevine (Moriondo *et al.*, 2015) has been undertaken through model intercomparison projects (AgMIP[7] and FACCE–JPI MACSUR[8]). These efforts have helped identify both the potential and the limitations of these tools for characterizing certain impacts. Possible future research to improve these tools include better accounting for high temperatures in certain processes (such as fruit set and quality), extreme events, and the effect of increased atmospheric CO_2 on plant function.

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[5] https://www6.paca.inrae.fr/stics.

[6] French National Research Agency.

[7] Agricultural Model Intercomparison and Improvement Project, https://agmip.org.

[8] Joint Programming initiative on Agriculture, Food Security and Climate Change – Modelling European Agriculture with Climate Change for Food Security, https://stics.paca.hub.inrae.fr/partenaires-et-projets2/projets-en-cours/macsur.

Other studies that are more focused on modelling processes, such as phenology and water balance, have also been carried out over the last 20 years. Duchêne and Schneider (2005) proposed an initial assessment of observed changes in climatic conditions and their impact on phenology and quality (represented by the potential alcohol of wine). In 2017, García de Cortázar-Atauri *et al*. produced an initial summary of the effects of climate change on grapevine phenology in France. Their research looked at changes already observed at different phenological stages (bud break, flowering and veraison) as well as harvest date. This study, which was carried out as part of the LACCAVE project, also predicted changes in phenology in all French winegrowing areas, based on different grape varieties (Chardonnay, Syrah and Cabernet Sauvignon), time horizons (2000, 2050, 2100) and greenhouse gas emission scenarios (RCP[9] 2.6, 4.5 and 8.5).

The other main process that has typically been studied in this context is water balance. Schultz and Lebon (2005) published one of the first studies on the subject. They explored possible changes in the water balance according to different evaporative demand scenarios and showed that grapevine could have high adaptability to future climatic conditions. Pieri and Lebon (2010) later simulated future changes in water requirements as part of the ANR CLIMATOR project[10] (Brisson and Levrault, 2010) and confirmed that, according to the scenarios used at the time, a general deterioration is unlikely. However, Lebon and García de Cortázar-Atauri (2014) showed a potential increase in severe water deficits and warned that further modelling work and experiments were needed to assess adaptation strategies to limited water resources. Future changes in water balance have since been systematically studied using crop models (e.g. Fraga *et al*., 2018; Yang *et al*., 2022).

In recent years, work on modelling grapevine function has been strongly influenced by emerging issues related to identifying the best strategies for adapting viticulture to climate change. A general summary of these issues is provided at the end of this chapter.

Recent work on developing climate indicators for viticulture

Climate indicators have played a dominant role in research on the impacts of climate change on viticulture. This work relies on so-called agroclimatic indicators, which are indicators calculated over periods determined by calendar dates (e.g. 1 April and 31 October; see figure I-1-1). These indicators (e.g. the number of frost days or the amount of precipitation over specific periods) can be used to assess and compare the effects of climate in different territories (here, winegrowing areas). However, these indicators are based on the assumption that the period of plant functioning (grapevine in this case) will not change over time, as the climate will be stationary. In fact, grapevine phenology has already been altered and it will continue to change (advance or lag).

Researchers have developed a new type of indicator to account for changes in the grapevine development cycle and its intraspecific variability (the level of earliness of grape

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[9] RCP: *Representative Concentration Pathway*. Each RCP reflects a representative greenhouse gas concentration trajectory through 2100. The Intergovernmental Panel on Climate Change (IPCC) established these scenarios in its fifth report.

[10] https://www.adaptation-changement-climatique.gouv.fr/centre-ressources/livre-vert-du-projet-climator.

varieties): ecoclimatic indicators (Caubel *et al.*, 2015). These indicators set the calculation period using the phenological stages (observed or simulated using a model) of the species or variety of interest. This means that the positioning of the stages and the length of time between two stages varies from one growing season to the next. This method provides information on the climate effects that are directly linked to crop growth and development during sensitive stages of the plant cycle. Critical thresholds can also be incorporated into these indicators, which reflect the ecophysiological response of each species. These thresholds mean the plant's responses to its environment can be taken into account and the impacts more precisely analysed (such as by setting 37°C as the critical temperature threshold for development).

Several studies have been carried out in recent years to further develop this method. For example, García de Cortázar-Atauri *et al.* (2016) proposed a conceptual framework to characterize changes in climatic conditions in French winegrowing areas by taking grapevine phenology into account (figure I-1-2).

This ecoclimatic approach makes it possible to describe changes in future climatic conditions in any winegrowing area in France. The main simulated impacts vary significantly depending on the time-horizon (2050 or 2100) and especially on the chosen emissions scenario (RCP):

- a general advance in phenology, with different levels of intensity between vineyards in the south and those in the north of the country;
- a significant and widespread increase in temperatures, particularly during the ripening period;
- disparate situations with regard to water stress, but with a significant deterioration in Mediterranean vineyards.

More recent studies have looked at these impacts in greater detail in different winegrowing areas (Marjou and García de Cortázar-Atauri [2019], in the Ventoux protected designation of origin – PDO area; Zito [2021], in the Burgundy area) and sometimes at a finer spatial resolution (Huard, 2021).

In recent years, research on changes in frost risk (Sgubin *et al.*, 2018 and 2019; Leolini *et al.*, 2018) has adopted the ecoclimatic approach to account for changes in the bud break date due to climate change. These studies noted that the quality of the phenology models used to calculate the bud break date is very important, because the probability (or not) of observing frost risk is strongly linked to the bud break date simulated by the models (Sgubin *et al.*, 2018). Ruling out such a risk appears very difficult (contrary to what was described in the CLIMATOR project, for instance), and this was demonstrated in 2021 and 2022 with exceptional frost episodes attributed to climate change (Vautard *et al.*, 2023).

Ecoclimatic indicators have also been used to understand certain trends observed in recent years (Bécart *et al.*, 2022; Meggio, 2022), shedding light on potential risks and how to adapt to them. For example, Bécart *et al.* (2022) used the GETARI software[11] (García de Cortázar-Atauri and Maury, 2019) to determine the climatic factors that may have affected grape quality in the Rhône Valley from 1969 to 2020. This research confirmed the major influence of different climate variables at different periods during the grapevine

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[11] Generic Evaluation Tool of Agroclimatic Indicators, https://agroclim.inrae.fr/getari.

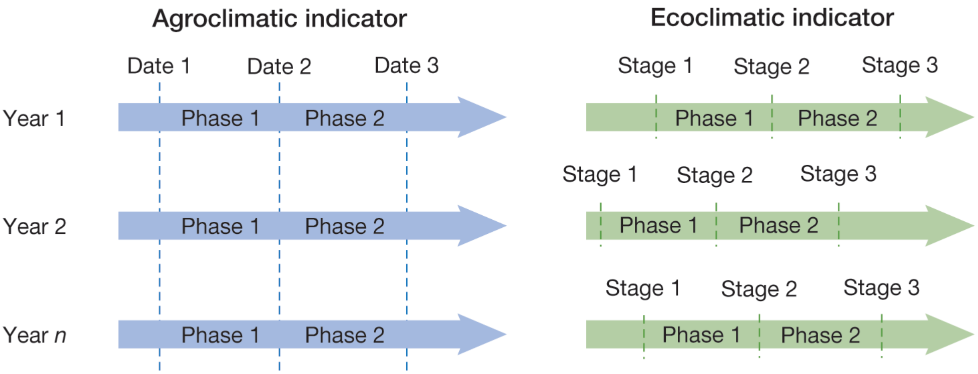

Figure I-1-1. Conceptual diagram of an agroclimatic indicator (left) and an ecoclimatic indicator (right). Agroclimatic indicators describe a period using two calendar dates (e.g. 1 January and 31 January) while ecoclimatic indicators use phenological stages.

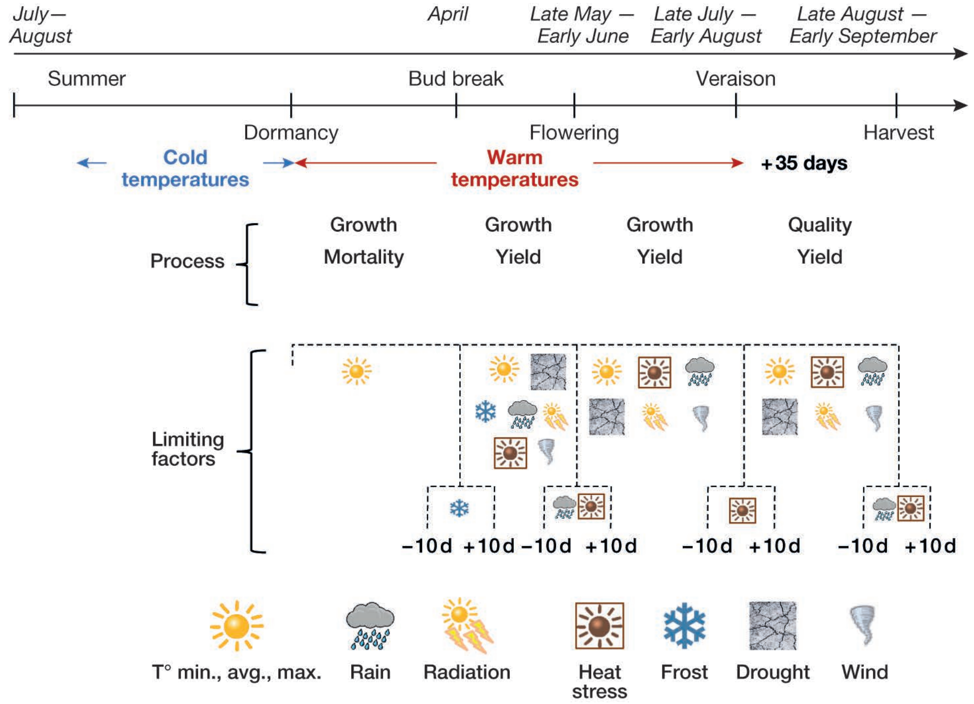

Figure I-1-2. Diagram for calculating ecoclimatic indicators for grapevine. Based on Marjou and García de Cortázar-Atauri (2019).

Several limiting factors were considered: minimum, average and maximum temperature values; total rainfall; total radiation; maximum temperatures above 30°C; frost; water deficit; and days with winds above 15 km/h. See annex 1 in Marjou and García de Cortázar-Atauri (2019) for the full list of calculated indicators. The values "+ 10 d" or "− 10 d" mean that the indicator was calculated during the period covering the 10 days before and 10 days after the phenological stage.

cycle on higher sugar content and lower acidity. It demonstrated how climatic conditions at certain periods affect plant function and potential yield. For example, the 200-berry weight was strongly correlated with temperature during the phase from fruit set stage to the end of berry growth.

Finally, grapevine adaptability was assessed by considering changes in its phenology and, consequently, its climatic suitability (climatic conditions that can ensure production and a certain level of quality). In 2010, Duchêne *et al.* published a groundbreaking study on the adaptability of several grape varieties in Alsace, showing that very late-ripening varieties would need to be developed to survive the sharp temperature increases expected during berry ripening (see box I-1-1 and figure I-1-3).

Morales-Castilla *et al.* (2020) explored grapevine adaptability on a global scale by leveraging its intraspecific diversity. A phenology model was adapted to 11 grape varieties and a set of indicators was selected during ripening to describe the best conditions for grapevine climatic suitability (see the article's supporting information for the full description). Their findings showed that climate change could substantially reduce viticultural suitability worldwide (the global winegrowing area would decrease by 56% with a 2°C rise in temperature and by 85% with a 4°C increase).[12] But the authors also showed that intraspecific diversity (represented in the article by the different levels of early ripening of grape varieties) could significantly reduce these impacts (from 24% to 56% at 2°C, and from 58% to 85% at 4°C). Finally, in early 2023, Sgubin *et al.* partially adapted the method used by Santos *et al.* (2012) by taking phenology into account to explore the potential impacts of climate change in Europe on viticultural suitability. They confirmed the trend towards a decline in current winegrowing areas and the appearance of new areas in northern regions, as well as the use of intraspecific variability as an adaptation strategy. But they also showed that these strategies could become less effective, especially if temperatures rise above the 2°C warming threshold.

Alongside these studies, initiatives have emerged in the various production sectors. The professional and technical community is striving to give producers and advisers information so they can better understand the impact of climate change in different winegrowing areas and to initiate discussions on adaptation strategies (field to regional scales). These initiatives include the ORACLE[13] and ClimA-XXI programmes[14] (see chapter II-4; box II-4-2), deployed at departmental level by the local chambers of agriculture; the CLIMENVI project[15] of the Centre–Val de Loire Region Chamber of Agriculture (box II-5-4); research on the Ventoux PDO winegrowing area (Marjou and García de Cortázar-Atauri, 2019; Huard, 2021; box II-5-3); and the Climadiag Agriculture Canari-France platform[16] developed by Solagro and Météo-France to produce countrywide impact indicators.

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[12] 12. The thresholds of 2 and 4°C temperature increases are often used in the scientific literature to represent climate changes without necessarily setting a time horizon. However, the general assumption is that 2°C corresponds to the warming that is likely expected in 2050, and 4°C to potential warming at the end of the century if current emissions policies (as of 2023) stay the same.

[13] 13. *Observatoire régional sur l'agriculture et le changement climatique* [Regional Observatory on Agriculture and Climate Change].

[14] 14. Climate and agriculture in the twenty-first century.

[15] 15. CLIMENVI: integrating climate change into the decisions made by winegrowers in the Centre–Val de Loire region (box II-5-4).

[16] 16. https://climadiag-agriculture.fr/.

Box I-1-1. An example of simulation of impacts on phenology

Phenology refers to the timing of periodic events, including major stages of vegetative and reproductive development, in a crop. During these stages, soil and climatic conditions, such as water and mineral availability, sunlight, and air humidity, have a major impact on the development of the canopy, flowers and berries, their number and volume, and the grape composition, and therefore on the wine produced. The transition between the main stages – dormancy break, bud break, flowering, veraison – is largely dependent on temperature conditions, and many models can predict the stages using only daily air temperatures. The general principle, which applies to many other plants as well as other living organisms, is to calculate the "sum of active temperatures": the difference between the average temperature and a baseline temperature, which is considered to be the critical threshold for species functioning, is cumulated from day to day.

These models, which vary in complexity, can be used to predict the different stages. It is now possible to use these tools and observed climate data or data from models simulating future climatic conditions to obtain, for example, an order of magnitude for temperatures during grape ripening in a future climate scenario, as illustrated in the figure below.

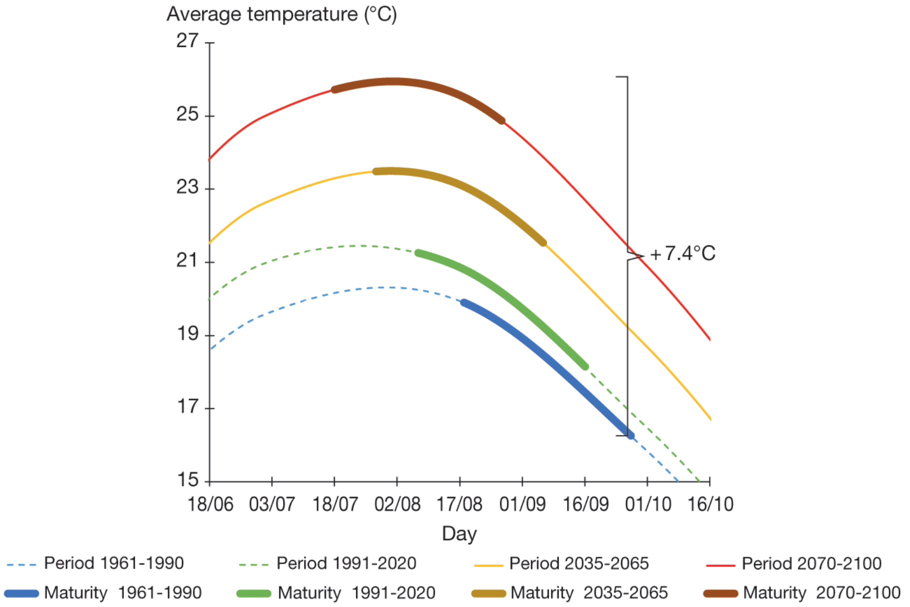

Figure I-1-3. Changes in average summer temperatures over 650 grids (8 × 8 km each) in France, where grapevine accounts for more than 5% of the total surface area of the grids.

Data through the end of 2020 were retrieved from Météo-France Safran. From 2021 on, they correspond to simulations with the CNRM-CM5/ALADIN63 model and the IPCC RCP 8.5 scenario. The veraison dates for Chardonnay were simulated and the ripening period shown corresponds to the following 40 days. This figure shows that the ripening period has shifted towards midsummer and that the temperatures are increasingly warmer at a given date. The result is a possible 7.4°C rise in temperatures during ripening by the end of the century.

Finally, the ClimA joint technology network (RMT ClimA)[17] brings together stakeholders involved in applied and targeted research, agricultural and rural development, and agricultural education to collaborate on adapting farms to climate change. All these initiatives connect institutions, industry players and regional stakeholders to develop and share findings and strategies based on approaches using agroclimatic and ecoclimatic indicators.

Recent work on grapevine modelling applied to climate studies

The initial modelling work described above has helped researchers characterize the various impacts of climate change on wine production. But this work has also highlighted the need for new knowledge to better describe how the winegrowing system as a whole (from the plant organ to the region) faces these new challenges. Recent research by the AgMIP initiative confirms the need to investigate the processes involved as well as how to integrate them into the models so they can best reflect the effects of what are sometimes extreme conditions on plants. A number of research projects are now under way in France, with the aim of better describing and representing the grapevine system and how the plant functions.

Better describing and understanding the role of water in plants

Better modelling of the function and architecture of grapevine roots is critical for improving the representation of the plant's adaptability to climate change, and more specifically to drought episodes. The grapevine system is highly complex, since the way it functions (particularly in terms of water) involves interactions between the aerial part (the scion variety) and the root system (the rootstock). Fichtl *et al.* (2023) proposed a conceptual framework combining water balance models and rootstock architecture descriptors. This framework should provide a better representation of how the system changes to cope with water stress, particularly during the plant establishment period. The authors suggested characterizing the main root architectural traits using phenotyping platforms and integrating this knowledge into plant-centred models. These tools will be useful for exploring plant behaviour in silico within a wide variety of environments and for selecting new rootstocks.

A better representation of the role of water in grapevine is also crucial for studying water stress and how it evolves with climate change. Recent studies have produced representations of the hydraulic structure in grapevine to analyse and predict the spatial distribution of gas exchange (HydroShoot model; Albasha *et al.*, 2019). This type of model and other research on canopy architecture (Prieto *et al.*, 2020) should facilitate efforts to evaluate grapevine function in greater detail and test hypotheses for adapting vineyard management to increasing environmental constraints, such as water deficit or extremely high temperatures.

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[17] The ClimA joint technology network is a group of experts in research, training and development to speed up R&D and knowledge transfer on adapting farms to climate change. https://rmt-clima.fr.

Better describing and anticipating changes in phenology

We have shown the importance of modelling phenology – a process that impacts the entire plant – in a way that directly integrates the climatic impacts in each winegrowing region and according to grape variety. Several dozen studies have been published in recent years that propose new models to simulate certain phenological stages (e.g. Parker *et al.*, 2020a), or to test existing models under new growing conditions (Wang *et al.*, 2020). Despite the robustness of most models, improvements are still needed to better characterize certain development stages, such as dormancy and post-dormancy, or their response to high temperatures. This should improve the characterization of certain impacts (e.g. the risk of frost around bud break), while reducing uncertainty about the choice of grape varieties in some at-risk regions.

Factoring in changes in health risks

In recent years, a number of grapevine disease modelling studies have explored the impact of climate change on host–pathogen interactions. Research by Zito (2021) highlights the complexity of the interactions between the host (in this case, grapevine) and the pathogen (in this case, powdery mildew) depending on the region. Zito nevertheless identified the value of mechanistic models for representing certain complex processes in system functioning (e.g. disease intensity). Castex *et al.* (2023) also studied future changes in pest pressure from *Lobesia botrana* (European grapevine moth or worm) on grapevine, and specifically how the synchrony between these two species could change in the future. Their findings showed that high temperatures could limit the number of generations of *L. botrana* in southern regions, while increasingly warm conditions in northern regions could support the emergence of a new generation.

Moving towards participatory modelling and the co-construction of adaptation strategies

Researchers are continuing to develop and test grapevine-adapted crop models in different situations. These models provide insights on increasingly complex issues, but they require a good level of understanding of both the model and the information entered (data describing the climate, soil, crop, crop management sequences and initial system conditions), which limits their use in certain contexts. The analysis by Moriondo *et al.* (2015) and, more recently, that by Knowling *et al.* (2021) take stock of the strengths and limitations of these models. Finally, Naulleau *et al.* (2022a and b) proposed a participatory framework for developing a grapevine yield model (in a Mediterranean climate), with the aim of using it to co-construct adaptation strategies in conjunction with water use (see chapters I-7, II-6). Researchers can use this type of approach, along with studies on multi-agent models developed in recent years, to explore adaptation scenarios at scales ranging from the farm to the region (Tissot *et al.*, 2020).

Limitations and future research avenues

All the studies described in this chapter, although not an exhaustive list, have made it possible to characterize with varying degrees of precision the past, present and future impacts of climate change on viticulture. Among the tools discussed, we have shown, for example, that agroclimatic indicators adapted to grapevine have limitations when it comes to factoring in changing climatic conditions, and therefore guiding adaptation strategies. But we have also noted other limitations and research avenues for the years to come.

All this research has brought to light new limitations, both in terms of methodology and knowledge. This is especially true of climate data, which are used as an input variable for calculating indicators and models. The scientific community working on climate has produced a huge number of data sets from various models based on different spatial and temporal scales and emissions scenarios. These data support more robust analyses and incorporate more situations, so that uncertainties within the calculation chain (model or indicator – climate model – climate scenario) can be better described and considered. Recent work by Sgubin *et al.* (2023) shows the importance of taking these uncertainties into account to improve result interpretation.

Better describing the soil, its components, the way it functions and its interactions with the plant (particularly via the roots) is a major priority going forward. Soil has been pinpointed as a fundamental part of the system, both in determining strategies for adaptation (as a reservoir of water and nutrients for plants) and mitigation (carbon storage) and in ecosystem service provision (biodiversity). There are major national and regional databases describing soil physical properties.[18] However, soil diversity must be better accounted for in crop models (such as STICS) or in calculation platforms (such as OpenFLUID[19]). Doing so would make it possible to explore issues such as irrigation management (with regard to water resources) or how viticulture could support carbon storage strategies. A major effort to pool databases (soil, climate, farming practices) will also be needed in the coming years to pave the way for new local adaptation strategies. Finally, better observation and modelling of changes in soil physical properties (particularly temperature changes) and interactions between plants and soil-borne microorganisms will be required to explore adaptation strategies, especially in terms of agroecological transition.

Another major limitation of these tools is the current state of knowledge on grapevine response thresholds. Most indicators and some model response functions use threshold values (e.g. maximum temperature for development; Merrill *et al.*, 2020), which describe critical plant response points. These values, often drawn from the literature and obtained from very old experiments, have their limitations (e.g. how representative they are when intraspecific variability is involved) and in some cases need to be confirmed or more precisely established (e.g. response thresholds to water stress). However, it can be complex and costly to set up the necessary experiments to understand these processes and determine these threshold values (Merrill *et al.*, 2020).

Finally, and related to the previous point, data access is becoming crucial to the proper evaluation and validation of these tools. Open observation databases are needed to properly explore certain questions. A great deal of work has been carried out in recent years on phenology data (see, for example, the TEMPO network portal[20]), but more

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[18] https://www.gissol.fr

[19] https://www.openfluid-project.org

[20] TEMPO is a national network of observatories in France that studies the phenology of the living world, https://tempo.pheno.fr.

needs to be done. A key point for the future will be to integrate observation data from winegrowing regions around the Mediterranean basin and in southern France, which could enable researchers to test these models and indicators under extreme conditions and assess their validity.

Climate change impact studies and the tools developed to perform them must incorporate knowledge from basic research (description of mechanisms) to produce robust data. Thinking about the use of these tools upstream will ensure that they are transferred and deployed under the best possible conditions to the organizations responsible for applied research and development (interprofessional organizations, technical institutes, chambers of agriculture). We need to set up training courses and forums for co-construction (as in Focus Area 1 of the ClimA joint technology network) to ensure they are used effectively in advising on and creating local adaptation strategies to tackle the challenges of climate change.

Chapter 2

VINEYARD SOILS AND CLIMATE CHANGE

Stéphane Follain, Étienne Fayolle and Amélie Quiquerez

Introduction

"Soil is a natural body that extends from the Earth's surface to a depth marked by the appearance of hard or loose rock that has not been significantly changed or marked by soil genesis. Soil can vary in thickness from a few centimetres to tens of metres or more. It is a part of the pedological cover (soilscape) that covers the entire Earth's surface. It usually comprises several horizons composed of organic and/or mineral constituents. This layered structure is the result of soil genesis and changes in the parent material. Intense biological activity (of roots, fauna and microorganisms for example) takes place in the soil" (AFES, 2018).

Globally, the arable land area is relatively small at around 5 billion hectares (FAO, 2021). In fact, nearly two thirds of the world's land cannot be farmed for a variety of reasons related to physical geography (e.g. unsuitable topography), climate (e.g. extreme temperatures or water availability, which hamper biomass production), and intrinsic soil characteristics (e.g. soils that are too thin, hydromorphic or with unsuitable chemistry). On a human scale, soil genesis processes are very slow, with only a few millimetres or centimetres of soil formed every millennium (Schaetzl and Thompson, 2015). This rate is much slower than losses from artificialization or erosion (Montgomery, 2007; Nearing *et al.*, 2017). This means that humans should consider soil as a scarce and non-renewable resource, despite its apparent abundance. The FAO estimates that around 33% of arable land worldwide is moderately or severely degraded and unproductive. In Europe, an estimated 13% of the soil surface is under threat (Borrelli *et al.*, 2017, 2020) and around 61% of land is degraded.[21] The state of soil, which is tied to global population growth and related needs, explains the tensions exerted on it and the rising number of conflicts stemming from its use. It should also be noted that agricultural production volumes are expected to increase by around 70% to 100% (Van Dijk *et al.*, 2021; Alexandratos and Bruinsma, 2012).

Although soil is a limited resource, it provides essential ecosystem functions and services (Haygarth and Ritz, 2009; Bünemann *et al.*, 2018). Among its many functions (figure I-2-1), soil is necessary for food, fibre and fuel production, as a habitat for organisms and for cultural heritage (FAO, 2015). However, soil faces numerous pressures that lead to a degradation in both quality and amount over time. Among the most critical pressures are erosion, compaction, artificialization, loss of organic carbon and nutrient imbalances that can compromise soil functions (FAO and ITPS, 2015; Montanarella *et al.*, 2016). These current degradation trends are a cause for concern, especially because, if no

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[21] https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard (Accessed 14/12/2023).

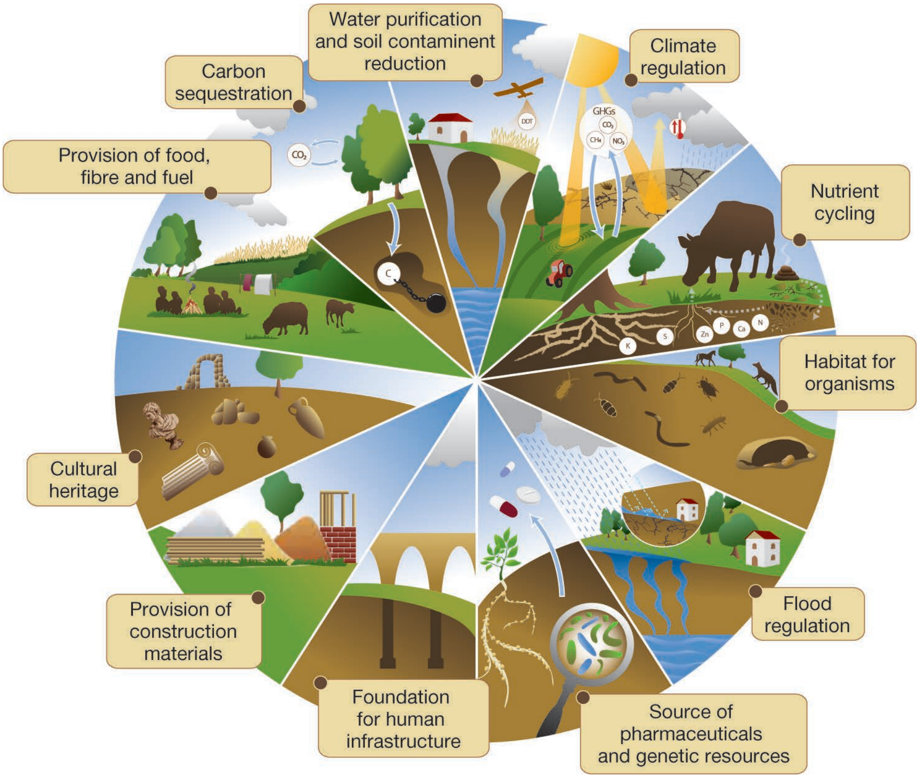

Figure I-2-1. Soil functions. Source: FAO, 2015.

efforts are made to reverse them, they will worsen with global change (IPCC, 2019). Many scientists have long said that protecting the soil is essential to the survival of our societies and will be a major and vital challenge over the coming decades (Blum, 1998; Lal, 2004).

Wine and grape production must tackle the challenge of adaptability in two complementary ways: by adopting and transitioning to farming methods that are efficient both in terms of production and soil protection,[22] and by adapting production systems to climate and socioeconomic changes.

To identify the challenges for vineyard soils in relation to climate change, the first step is to analyse the specific characteristics of vineyard soils and the particular functions they support. Efforts can then be made to predict future dynamics and consider the sustainability of wine production.

The specific characteristics of vineyard soils

Vineyard soils vary in type and properties. These variabilities are highly dependent on climate and other soil formation factors. That said, they do share common pedological features, and they all provide essential functions and services.

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[22] https://sdgs.un.org/goals (Accessed 14/12/2023).

Soil and climate variability

Although the soil plays a vital role in the typicity of a terroir, descriptions of soil are often general and reductive. This can give the impression that there is little variability in the soils suitable for viticulture in mainland France, when in fact, there is a wide range of soil types where grapevines are grown (Fanet, 2001). Examples include Rankers on schist in Roquebrun and Berlou (Saint-Chinian AOC), which are locally very thin and sometimes have pH values below 4.0; Peyrosols on the alluvial terraces of Châteauneuf-du-Pape, with stoniness exceeding 60%; and Calcosols, often with a high chlorosis potential, on limestone and marl in Côte de Beaune areas (Côte-d'Or). Given this range, it might seem that grapevine can be produced on any type of soil. This is essentially the case, provided that the soil can fulfil the functions required for plant production, that the planting material is suitable, and above all that the climate is favourable. Climate is the primary factor determining the spatial distribution of wine production (Gladstones, 1992; Jones, 2006), which explains the popularity and predictive power of climatic indices such as the heat sum or Huglin index (1978), as well as multi-index and spatial approaches such as the multicriteria climatic classification system (Tonietto and Carbonneau, 2004). Climate is also one of the main factors involved in soil genesis (Dokuchaev, 1899; Strakhov, 1967) and in regulating soil functions.

This strong interaction between soil and climate explains the emphasis that soil scientists place on the local soil and climate. Understanding the characteristics of the soil and climate where the grapevines will grow is crucial to optimizing plant growth conditions and managing wine production. By knowing the local soil and climate, stakeholders can choose the most suitable planting material and farming practices to best leverage the interactions between soil and climate. It is important to not confuse the idea of local soil and climate with the term "soil climate", which refers to the soil temperature and moisture conditions, which vary during the year (Baize, 2004).

Climate change will impact local soil and climate, creating conditions for wine production that may be more or less favourable. Some traditional production areas could become unsuitable due to water stress or excessive heat, as is feared in southern France. Meanwhile, opportunities for new terroirs could arise in more northerly areas or at higher altitudes. However, these new terroirs will have to build an identity specific to their wine production.

A comparison of current production areas based on French soil property maps (Gis Sol, 2011) shows that domestic production occurs in soils with varying properties. However, a large proportion (by volume) of this production is carried out on sola with carbonate accumulation or a pH close to neutral, as well as balanced to clayey textures, as can be seen throughout the Languedoc area (figure I-2-2). This soil "signature" will likely change as production areas shift from southern to northern France. Such a shift at the national level will still allow production on calcareous soils, as is currently the case in many vineyards in the Loire Valley, but also on new calcareous soils, which is seen with the Calvados protected geographical indication (PGI) in Normandy. Moreover, although national production already takes place across various terroirs with acidic pH soils, such as Alsace, Beaujolais and Corsica, a northward shift will increase the quantity produced in these acidic pH soils, such as those found in the crystalline massifs (including the Armorican Massif and Massif Central), as well as in all soils with predominantly silty textures, inherited from the loess belt of northern Europe (Lautridou, 1985).

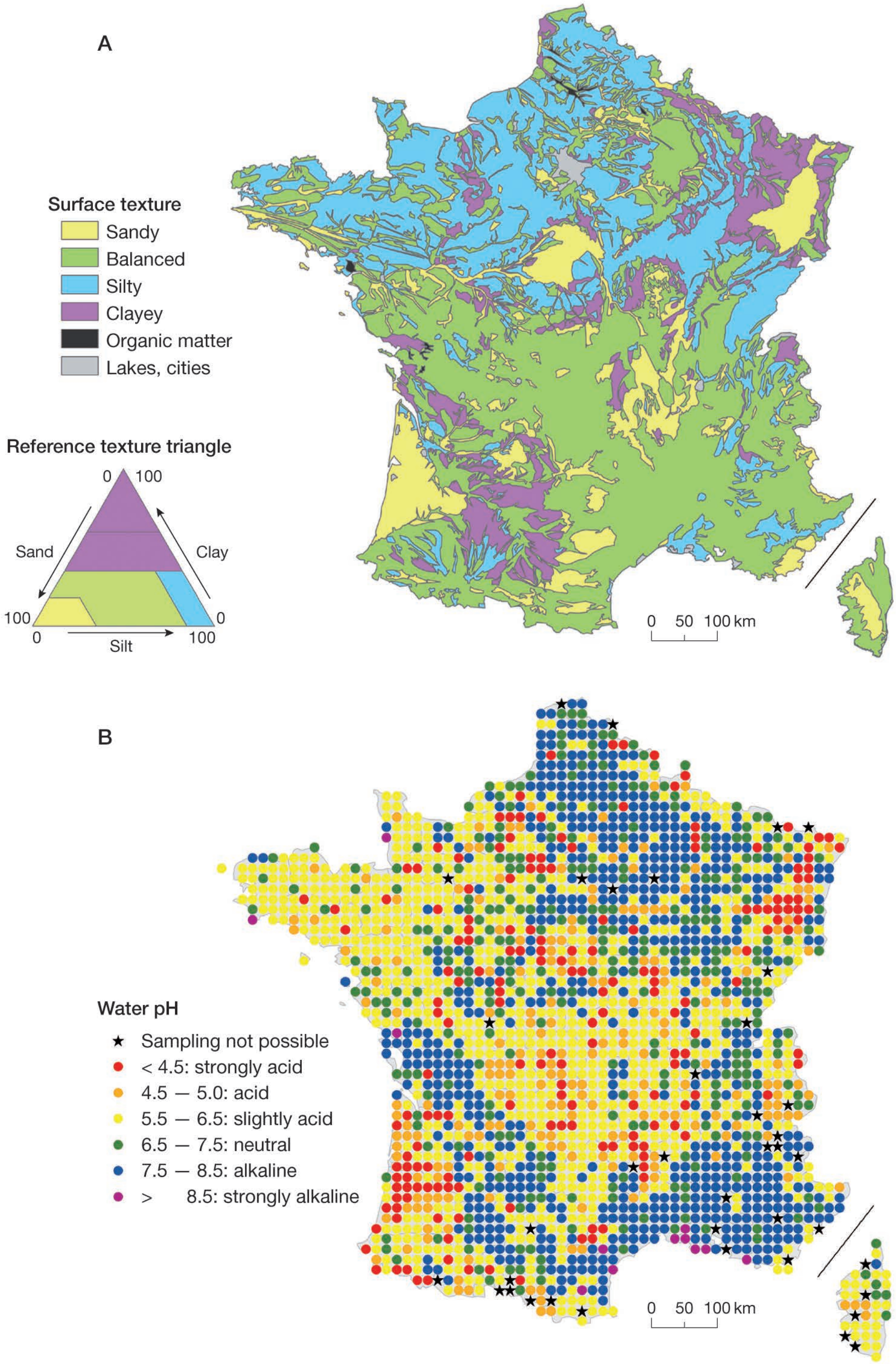

Figure I-2-2. Soil texture maps (A) and water pH maps (B) of the upper soil horizons in mainland France. Source: Gis Sol (2011).

Growers will turn to cultivating in the Massif Central and other mountainous areas in an effort to find milder temperatures at altitude. In short, the possible shift of winegrowing northwards and to higher altitudes in response to climate change is likely to result in cultivation under different soil and climate conditions, and therefore variable local soil and climate conditions. Advances in grapevine breeding are certainly needed to adapt to these new conditions (see chapter I-5).

Common soil characteristics

Although there is a high degree of soil variability among production areas, many vineyard soils have some characteristics in common. As a crop, grapevine has adapted to soil and climate conditions that are often difficult or even hostile to other crops. Grapevine's considerable plasticity means it can adapt to difficult soil conditions, such as nutrient-poor, shallow or very stony soils or soils with a low organic matter content. This plasticity and adaptability explains why in many rural areas, grapevine has historically been a go-to crop in areas that are difficult to access or unsuitable for other types of farming (Garcia, 2010). Grapevine has been able to flourish in these areas over time, growing on steep hillsides and in shallow soils (Burgundy), on arid land and in stony soils (alluvial terraces in the Rhône Valley), and in mountainous areas (Savoy). The choice was often made to plant on hillsides in these areas. These cultivated hillsides are subject to erosion processes that modify the nature, thickness and spatial distribution of the soil over time, which can accentuate the restrictive edaphic conditions described above. Due to the combined action of run-off and tillage, soil on hillsides is subject to sediment dynamics that result in a redistribution of soil along the slopes (Follain, 2015), and sometimes permanent loss of fine soil and nutrients to river systems. Over time, this soil redistribution leads to changes in soil properties, including hydrodynamic, physical and chemical properties. This means that sediment dynamics can have a profound effect on soil and climate conditions and the quality of the wines produced.

The relationship between the current specific characteristics of vineyard soils and long-standing use conflicts must be factored in when establishing future terroirs, as there is no guarantee that other crops or land uses will not push out vineyard production.

A final common feature of vineyard soils is their state of degradation, ranging from moderate to severe (Rodrigo-Comino, 2018; Rodrigo-Comino *et al.*, 2020). They can often suffer from extremely low organic matter stocks, low biodiversity, compacted soils, or high concentrations of metals and other contaminants, etc. This degraded condition makes vineyard soils more vulnerable to climate hazards.

The functions and services associated with vineyard soils

When it comes to agricultural production, the concept of function is similar to that of service, in that the direct beneficiary is known. To simplify things, from here on, we will use the word "function". The primary soil functions of interest are those that support yield and berry quality, including providing physical support for the grapevine, supplying water and nutrients to the plant and providing a habitat for various organisms.

These functions are related to biology or ecology. In addition to these functions, which are closely related to the concept of soil fertility, there are also abiotic functions, such as those that contribute to the idea of terroir, heritage and product image.

Non-ecological functions

In winegrowing, the heritage and cultural value of land is a major consideration. Vineyards and the landscapes associated with them have been built up over a long period of time, and they reflect a particular way in which human societies have developed an area. As such, these areas contribute to the cultural and historical identity of a place. For example, the specific way in which land is divided into fields in Burgundy (France) has been shaped by humans over centuries, creating a unique cultural heritage, with "*climats*" that are emblematic of this special relationship between wine and place (Garcia, 2010). Like Burgundy, the winegrowing areas of Douro (Portugal), Cinque Terre (Italy), Lavaud (Switzerland), and Saint-Émilion and Champagne (France) are now listed as protected world heritage sites, a status that attests to the importance of their heritage function.

Protecting and enhancing vineyard soils is also becoming a major heritage and cultural concern. These soils help to preserve a region's know-how, landscape and cultural identity while also promoting the high-quality wines produced there.

Physical support

The ability of the soil to provide physical support can be quantitatively assessed by measuring soil thickness, or more precisely, the volume of soil that living organisms can access. However, for grapevine (as for many perennial plants), considering this volume alone is an imperfect approach. This is because when the soil volume is low, it is the relationship between the soil volume and the properties of the underlying bedrock that is important. If the bedrock cannot be colonized by the roots, rooting is limited to the surface soil (thereby increasing lateral competition between vines). However, if the bedrock contains cracks or fissures, plant survival will depend on the total capacity of the soil–subsoil continuum. Furthermore, in addition to soil volume, soil stoniness (quantity of coarse elements larger than 2 mm) and texture (proportion of different sizes of particles) must be taken into account. These properties have a significant impact on the grapevine's rooting capacity and the soil's capacity to store water and nutrients. For example, the water capacity per unit volume of Peyrosol soils, such as those found on the alluvial terraces of the Rhône Valley, will be limited by their high stoniness (> 60%).

The support function of soils is currently threatened by soil erosion processes (both water and soil erosion), which cause land losses that are often critical in hillside vineyards, even leading to the gradual and irreversible disappearance of hillside soils. In these conditions, vine growth can become severely stunted (figure I-2-3). In fact, stunted growth is a marker of erosion, and the stock unearthing method has been used to quantify soil degradation rates over several decades (Brenot *et al.*, 2008; Casalí *et al.*, 2009). With this method, the callus that grows around the graft is used as a passive marker of topographical variations. Rootstock unearthing provides an estimate of the amount of soil that has been eroded from the vine since the planting year. Erosion rates estimated using this method for a set of vineyard plots in the Hérault, Burgundy and Bordeaux regions

(Brenot *et al.*, 2008; Paroissien *et al.*, 2010) ranged from 10 to 15 metric tons per hectare per year, corresponding to an average loss of around 1 mm of soil per year. The loss of fine soil through water and soil erosion on hillsides can change soil fertility, biodiversity and support capacity. Conversely, the foothills of these areas are often richer and more fertile, which can lead to higher plant vigour and higher yields.

Figure I-2-3. Unearthed vine roots in Languedoc. © Stéphane Follain.

Water and nutrient supply

Climate change includes changes in temperature and the amount of water available to vines, which are key factors in managing yields and berry quality. It is also important to remember the often overlooked point that when water uptake stops, nutrient flow stops as well: a change in water supply results in a change in nutrient supply. We will not go into detail here on nutrition and water stress, the effects of which are presented in chapter I-3. Instead, we will focus on the role of organic matter in vine nutrition (figure I-2-4). The mineralization and humification of organic matter by the soil microbiota modulate nutrient availability. However, vineyard soils are known to have low levels of organic matter compared to land used for other purposes (Meersmans *et al.*, 2012). There are two reasons for this. One is the spatial distribution of vineyards, which are often on hillsides and thus exposed to soil loss through water erosion. The other is the way in which weeds and organic matter are managed in vineyards: many winegrowers no longer leave post-harvest plant matter in the fields or apply manure, and mechanical weeding has been largely replaced by chemical weeding for a long period (see chapter I-6).

Recent changes in weed control and organic matter management are beneficial for replenishing organic matter stocks in vineyard soils. In addition to improving grapevine nutrition and supporting cultural heritage, organic matter management can contribute to carbon sequestration and the 4 per 1000 initiative.[23] Such efforts are key because soils are impacted by global change and provide an opportunity to manage these changes. However, managing organic matter will require accommodating changes in soil moisture and temperature conditions. These two factors are catalysts for microbial activity. All other parameters being constant, climate change will alter the mineralization and humification dynamics of organic matter. This in turn will alter the soil's organic matter stock and therefore its physical and chemical properties and nutrient availability for the vines. Finally, considering the strong dependencies between microbial activity and the dynamics of carbon, nitrogen and other nutrients, fertility benchmarks will need to be revised in the future.

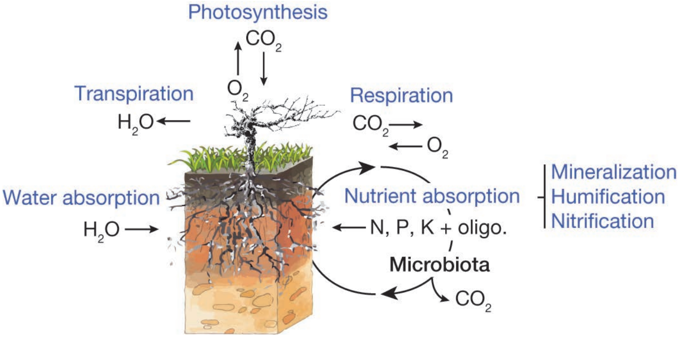

Figure I-2-4. Grapevine nutrition. Source: Follain (2014).

From mapping terroirs to mapping functions

As defined by the International Organisation of Vine and Wine (OIV, 2010), "'Terroir' includes specific soil, topography, climate, landscape characteristics and biodiversity features". Terroir is closely bound to the local area and geography, and there is a need to understand its variability (Vaudour, 2002). Given that the abovementioned characteristics of terroir are known locally, various studies have advanced knowledge on terroir–vineyard–wine relationships (Morlat, 1989; Van Leeuwen and Seguin, 1994) – in other words, the relationships between soil properties and functions, water and nutrient supply to the vine, and berry and wine properties.

Set up in 1935 by the French National Institute of Quality and Origin (INAO) to guarantee the quality and designations of origin of wine (Barham, 2003), the French labelling system (known as *appellation d'origin côntrollée*, or AOC) originally imposed mainly administrative boundaries. Today, delimitations and zoning increasingly take into account variations in the biophysical environment. This allows for more technical approaches to be developed based on the recording and quantification of environmental variables in the terroir's wine-growing system in order to differentiate between natural terroir units (Laville, 1993) or basic terroir units (Morlat, 1989). Carbonneau (2001) used these approaches as a starting point

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[23] The international 4 per 1000 initiative, launched by France on1 December 2015 at COP21, aims to show that agriculture, and especially agricultural soils, can play a crucial role in food security and climate change, https://4p1000.org.

to create viticultural terroir units, which include interactions with grape varieties and viticultural and oenological technologies. Rather than focusing on a division of space based on environmental variables, researchers are now accounting for soil functions through soil functional units (Fayolle *et al*., 2019). Applying these functional approaches should make it possible to identify and manage changes in soil–vine–climate relationships.

Conclusion

Agricultural soil is a scarce and finite global resource. Like all agricultural production, viticulture will have to strike a balance between using and preserving this resource. Sustainable land use must be addressed by taking climate and socioeconomic change into account. Some terroirs will see grapevine cultivation disappear, while others will have to manage it with an approach that uses fewer chemical inputs and less energy (from fossil fuels at least) while maximizing biotic and abiotic interactions.

CHAPTER 3

EFFECTS OF RISING TEMPERATURES AND WATER DEFICIT ON GRAPEVINES

Cornelis van Leeuwen, Thierry Simonneau and Chloé Delmas

Introduction

Just like with any other crop, grapevine physiology is affected by abiotic factors such as temperature, water and nutrient availability, sunlight, humidity and atmospheric CO_2 (Jackson and Lombard, 1993). Unlike with other crops, grapevine production value depends more on selling prices (related to the quality and reputation of the wine produced) than on yields. The price of a bottle of wine varies more (from a few euros to hundreds of euros) than yields do (from 3 to 30 metric tons per hectare). Accordingly, assessing the effects of climate factors on production quality is just as important as doing so for yield. Climate change is causing temperatures to rise in all winegrowing regions and intensifying water deficit in most production areas. These changes can substantially alter grapevine phenology and physiology as well as interactions between the grapevine and pests and pathogens. These issues are all the more pressing given that increasingly intense and frequent droughts will further amplify the effects of global warming. Drought conditions cause transpiration to drop, which deprives the plant of the physical cooling effect of water evaporation. In this chapter, we attempt to untangle the different impacts of heatwaves and droughts, although the two do tend to occur simultaneously in vineyards.

The main effects of rising temperatures on grapevine behaviour

Temperature strongly influences grapevine behaviour and major processes such as photosynthesis. Rising temperatures lead to phenological advance and can also cause changes in yield and impact both primary and secondary metabolites in grapes.

Photosynthesis

Photosynthesis is the process by which plants convert light energy into chemical energy in the form of organic compounds. These compounds play fundamental roles at every level, from establishing plant structures to supplying energy needed by all living cells and supporting sugar and organic acid accumulation in grape berries.

Although photosynthesis mostly depends on the amount of sunlight captured by leaves, it is highly sensitive to temperature. This complex process relies on a cascade of enzymatic reactions that are activated by both light and an increase in temperature (Bernacchi *et al.*, 2001). Various studies have sought to characterize the impact of temperature on the maximum photosynthetic capacity when there are no other limiting factors such as sunlight or soil water availability. As expected, a moderate temperature rise increases maximum photosynthesis permitted by the light conditions (figure I-3-1). However, when temperatures exceed an optimum level of around 30°C, this positive effect of temperature disappears (Greer and Weedon, 2012) and becomes negative. Given that climate change will cause this threshold to be exceeded more and more often, we can expect to see a marked reduction in photosynthesis.

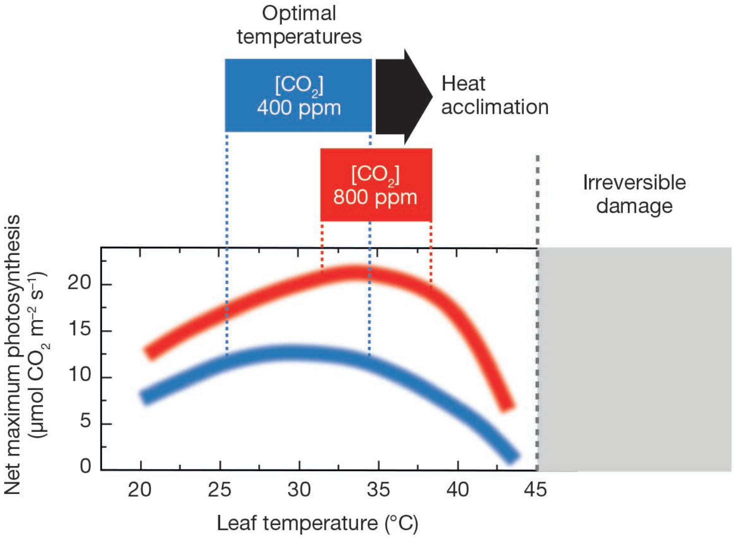

Figure I-3-1. Effect of leaf temperature on maximum photosynthetic capacity (when not limited by light or soil water availability).

The optimum temperature varies according to average plant growth conditions: an average increase in temperature shifts the response in the direction indicated by the red arrow; a rise in atmospheric CO$_2$ shifts the photosynthesis response from the blue curve (for 400 ppm CO$_2$) to the red curve (for 800 ppm CO$_2$). Based on Greer and Weedon (2012) and Greer (2018).

When the temperature increase remains moderate (around 10°C above the optimum), photosynthesis losses remain reversible (Edwards *et al.*, 2011), as the main limitation relates to the diffusion of CO$_2$ from the atmosphere into leaves. This diffusion takes place through the stomatal apertures located on the surface of the leaves, which close under the effect of the drop in relative humidity induced by a rise in temperature (Greer, 2018). As soon as the heatwave subsides, the stomata open up again and photosynthesis losses remain limited. If the heatwave is prolonged, the plant acclimatizes and the optimum temperature rises, which again limits the effect of a heatwave on photosynthesis. This acclimatization can also be observed under the effect of rising atmospheric CO$_2$ concentrations (Greer, 2018). However, the current rate of rise in atmospheric CO$_2$ concentrations will only slightly increase the optimum temperature.

When temperatures rise very high (above 45°C or so), the damage to the biochemical components involved in photosynthesis (specifically the photosystems and membranes; Sun *et al.*, 2017) becomes irreversible (Wise *et al.*, 2004). Damage worsens under conditions of severe water stress and when sunlight is high in summer. Shade can reduce the damage (Greer *et al.*, 2011). However, if no measures are taken to mitigate extreme temperatures, photosynthesis losses persist after the heatwave with major expected impacts for the current growing season or the following year's harvest, and even for the vineyard's long-term survival.

Vegetative growth

Temperature affects the vegetative growth of plants in addition to many other processes. Higher temperatures promote growth up to a certain threshold, beyond which growth is reduced (Keller and Tarara, 2010) or even inhibited according to a response curve that is well described by the Arrhenius law (Parent and Tardieu, 2012). Many species follow this curve, with an optimal temperature threshold for growth that varies little within the same species, but more between species (from 25°C to 35°C; Parent and Tardieu, 2012) depending on the climates under which the species evolved.

Experiments to separate the effect of temperature from that of humidity are fairly rare, particularly for perennial plants where experiments under controlled conditions are more complex. Under natural conditions, heatwaves cause a sharp drop in humidity due to the physical properties of the air. Leaf growth is very sensitive to humidity and is inhibited by the atmospheric water deficit (see the "Shoot growth" section below).

Rising temperatures therefore have parallel effects on photosynthesis, which is required for organic compound production, and on the growth of the vegetative parts, which uses those compounds. It would be logical to assume that the impact would be low, because of the balance that is maintained between the source and sink for photosynthesis products. However, higher temperatures speed up photorespiration as well as leaf and root respiration, affecting both source and sink activity, so the overall effect is negative (Escalona *et al.*, 2012). Extreme heatwaves intensify this imbalance by irreversibly damaging the leaves (Edwards *et al.*, 2011; see box I-3-1). This damage lowers the plant's carbon reserves (Kliewer *et al.*, 1972), which affects certain stages of yield development (see the "Yield" section below) and threatens vineyard sustainability (Smith and Holzapfel, 2009).

Phenology

Temperature has a decisive effect on plant phenology (Cleland *et al.*, 2007). By reconstructing past temperatures using harvest dates (Chuine *et al.*, 2004) and developing phenological models, we predict the possible future impact of temperature on plant phenology.

Changes already observed

An extensive series of phenology observations in the region of Alsace (France) showed that rising temperatures triggered by climate change caused substantial phenological advance in grapevine (figure I-3-2). Over a period of 70 years, bud break shifted forward by 10 days, flowering by 23 days, veraison by 39 days and harvest date by 25 days in Alsace. Similar trends have been reported in many winegrowing regions around the world (Van Leeuwen and Darriet, 2016). When bud break occurs earlier, vines are exposed to a longer period of spring frost risk, although it is not possible to be certain whether the actual risk of frost will increase or decrease (Sgubin *et al.*, 2018; see also the discussion of frost risk later in the chapter). When veraison occurs earlier, not only are bunches exposed to higher temperatures due to climate change, but ripening occurs at a time of year when temperatures are already higher, as shown by Molitor and Junk (2019). These authors noted that for each degree of temperature rise due to climate change, phenological advance leads to a temperature increase of around two degrees during the ripening period. This shift has a strong effect on the composition of both primary (Duchêne and Schneider, 2005) and secondary (Spayd *et al.*, 2002; Van Leeuwen *et al.*, 2022a) metabolites in grapes, and has a major impact on the quality and character of the wines produced.

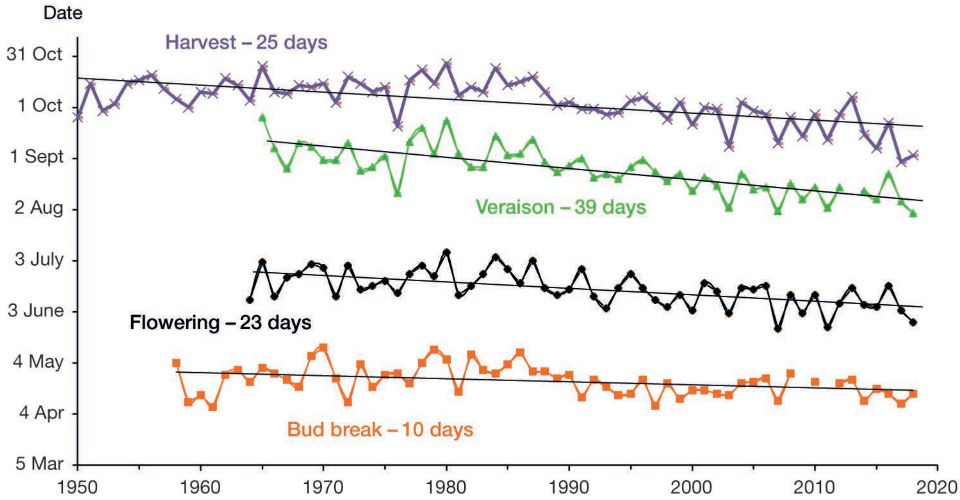

Figure I-3-2. Changes in phenological stages in Alsace from 1950 to 2020. Source: Data from 1950 to 2005 published by Duchêne and Schneider (2005), supplemented by E. Duchêne for 2005 to 2020.

Future shifts in grapevine phenology

Many models have been developed to simulate grapevine phenology, including the Grapevine Flowering Veraison (GFV) model (Parker *et al.*, 2011 and 2013) and the Grapevine Sugar Ripeness (GSR) model (Parker *et al.*, 2020a). It is possible to predict future changes in grapevine phenology using these models and temperature projections for different greenhouse gas emission scenarios. All the projections agree that phenology will continue to advance. An example for the Champagne region is given in figure I-3-3 (based on Parker *et al.*, 2020b).

Yield

A heatwave can affect all yield components. Extremely high temperatures one year (when inflorescences start to develop) can reduce the fertility (number of bunches per shoot) of the next year's harvest. This effect is probably linked to strong competition for photosynthesis products between vegetative and reproductive growth, which both have high carbohydrate demands when temperatures rise (Lebon *et al.*, 2008). Vigour control combined with a reduced fruit load could limit this competition.

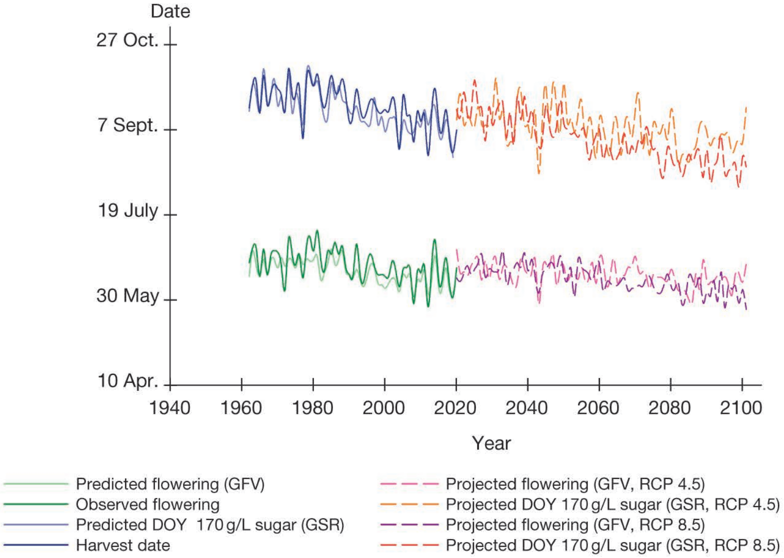

Figure I-3-3. Observed dates of mid-flowering (dark green) and harvest (dark blue) for the historical period, and predicted dates for mid-flowering (light green) and when the sugar content of the grapes will reach 170 g/L (light blue) in the Champagne region. Projected dates of mid-flowering for the end of the twenty-first century (dashed red line) and dates when sugar levels will reach 170 g/L (dashed orange line) for the RCP 4.5 greenhouse gas emissions scenario. GFV: grapevine flowering veraison; GSR: grapevine sugar ripeness. Source: Parker *et al.* (2020b); RCP: representative concentration pathways.

The number of flowers per inflorescence is also very sensitive to an excessive rise in temperature (Ebadi *et al.*, 1995), particularly if it occurs very early (Keller *et al.*, 2010). If temperatures rise above 35°C during the day around flowering, ovule fertility drops, which hampers fertilization (Kliewer, 1977) and reduces pollen performance (Rajasekaran and Mullins, 1985). Once again, one of the likely causes is that these processes are highly dependent on carbon reserves (Lebon *et al.*, 2008; Greer and Weston, 2010), and these reserves are negatively affected by heatwaves (see "Vegetative growth" above). When carbon reserves fall too low due to an increase in temperature, higher rates of abscission can occur during or shortly after fruit set (Greer and Weston, 2010; Pagay and Collins, 2017).

Finally, when average temperatures exceed 30°C during the year of harvest, the final berry size and weight decrease (Hale and Buttrose, 1974; Greer and Weston, 2010). This effect is particularly marked when the temperature rise occurs before ripening (Matsui *et al.*, 1986) and can be partly explained by cell enlargement being blocked in the berries during their herbaceous growth phase and until veraison (Rienth *et al.*, 2014). However, high temperatures also lead to greater water loss in both the plant and berries, which can then wither, reducing their volume without necessarily reducing the sugar content (Ollat *et al.*, 2002). Where temperatures rise the most – such as around bunches most exposed to the sun (up to 18°C higher than the air temperature) – berries can burn, leading to significant crop losses (Gambetta *et al.*, 2021; see box I-3-1).

Finally, a review of several studies showed that the negative effects of global warming on yield are mostly due to the increase in the frequency of heatwaves rather than increases in average temperature (Sadras *et al.*, 2017).

Grape composition and primary metabolites

Grape and wine composition has changed dramatically over the last four decades. Until the end of the twentieth century, low sugar and excess acidity in the grapes was a recurring problem in many winegrowing regions, leading to the widespread use of practices such as chaptalization (where sugar is added to the must to achieve the desired degree of alcohol in the wine). Today, however, winegrowers must contend with sugar levels that are too high and acidity that is too low.

Changes already observed

Since 1984, Dubernet, a specialized laboratory in the Languedoc region, has been calculating the average alcohol content, pH levels and total acidity of all young wines analysed for a vintage. Their results show that the alcohol levels of wines in this region have risen from 11% to 14%, acidity has fallen by 1.5 g of tartaric acid/L and pH has risen from 3.5 to 3.75 in 40 years (figure I-3-4). Similar trends have been reported in winegrowing regions around the world (Schultz, 2000; Jones *et al.*, 2005; Ollat *et al.*, 2017). Of course, this shift is not just the result of climate change, but also includes changes in the grape varieties planted, the introduction of clones that produce more sugar, changes in grapevine management systems and the leaf-to-fruit ratio, as well as the choice of harvest dates. New studies are needed to assess how much of the change in grape composition at maturity is attributable to climate change.

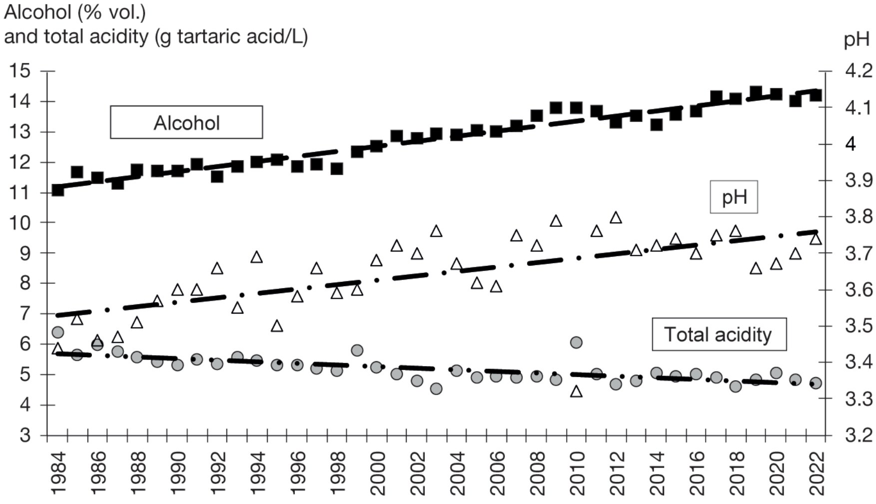

Figure I-3-4. Changes in the composition of red wine produced in the Languedoc region from 1984 to 2022. Each point represents the average of thousands of wine analyses just after alcoholic fermentation. Data: Dubernet laboratory, Montredon-des-Corbières, France.

Sugar content trends based on temperature and atmospheric CO_2

Several models have been developed to simulate sugar accumulation in grapes (Dai *et al.*, 2009; Parker *et al.*, 2020a; Suter *et al.*, 2021). They can be used to predict changes in grape sugar content for different greenhouse gas emission scenarios (Parker *et al.*, 2020b; figure I-3-4). Changes in grape composition will likely continue in the coming years. Few studies have explored the effect of rising atmospheric CO_2 levels on grape sugar content. The initial results of a FACE[24] experiment in Geisenheim (Germany) did not appear to indicate a major effect of this parameter (Wohlfahrt *et al.*, 2021), but it should be noted that the increase in the atmospheric CO_2 content was only 20% in this trial.

Grape composition and secondary metabolites

The quality and typicity of a wine largely depends on the secondary metabolite composition at the time of harvest. Temperature has a major effect on the presence and concentration of these compounds in the grapes.

Temperature strongly influences phenolic compound levels in grapes

Temperature has a very clear effect on phenolic compound accumulation in grapes, particularly anthocyanins. Grapes accumulate lower levels of anthocyanins if temperatures – especially night-time temperatures – are high (Kliewer and Torres, 1972). While many studies are based on leaf-removal trials, it is difficult to separate the effect of light from that of temperature in these types of experiments because the bunches are both warmer and exposed to more sunlight. Spayd *et al.* (2002) conducted an innovative experiment in which they cooled bunches that had their leaves removed and warmed bunches that still had their leaves. The researchers were able to clearly establish that direct light exposure increases anthocyanin concentrations, whereas high temperatures reduce them. Gouot *et al.* (2019a) described mechanisms that may explain the effect of high temperatures on phenolic compound synthesis and degradation.

Effect of temperature on grape and wine aromas

Temperature also has a strong effect on aroma precursors in grapes and wine aromas (Van Leeuwen *et al.*, 2020). High temperatures reduce herbaceous aromas induced by methoxypyrazines (Koch *et al.*, 2012) and 1,8-cineole (Poitou *et al.*, 2017), for example. However, they increase cooked fruit aromas (Pons *et al.*, 2017) as well as compounds that induce a complex ageing bouquet, such as dimethyl sulfide and aromatic heterocycles (Le Menn *et al.*, 2019). Volatile thiols (fruity aromas) tend to be negatively impacted (Wu *et al.*, 2019), while the effect of temperature on monoterpenes varies (Duchêne *et al.*, 2016). The effects of temperature on grape and wine aromas are summarized in table I-3-1.

The effect of temperature on secondary metabolites is discussed in more detail in the next chapter.

Frost risk: a complex phenomenon

Earlier budburst extends the spring frost-risk period for grapevine. However, the frequency of frost damage also depends on the date of the last frost, which itself has shifted earlier in most regions. According to Sgubin *et al.* (2018), the risk of spring frost for grapevine will increase in continental vineyards (Burgundy, Champagne), remain stable in Atlantic vineyards (Bordeaux, Cognac, Val de Loire) and decrease in southern vineyards (Côtes du Rhône, Languedoc, Provence). However, the authors noted that these predictions are highly uncertain because of the difficulty of modelling vine budburst. Gavrilescu *et al.* (2022) also highlighted difficulties in predicting frost risk.

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[24] Free-air CO_2 enrichment.

Table I-3-1. Effects of vine water deficit and increased air temperature on aromatic compounds in grapes and wines. Source: Van Leeuwen *et al.*, 2020.

	Aromatic compound or family	Increase in air temperature	Water deficit
Vegetal and peppery aromas	IBMP	Decrease	Decrease
	(−)-rotundone	Decrease	Decrease
	1,8-cineole	Decrease	Decrease
Other monoterpenes		Variable effect	Variable effect
Volatile thiols and C_{13}-norisoprenoids	Volatile thiols	Decrease	Increase if moderate deficit
	TDN	Increase	Increase
	Tabanones	Increase	Increase
	Other C_{13}-norisoprenoids	No effect	Increase
Cooked fruit aromas		Increase	May be increased by dehydration
Esters		Not yet studied	Increase
Other compounds	DMS	Increase	Increase
	Red wine ageing bouquet	Likely to increase	Increase
	O-aminoacetophenone	Not yet studied	Increase
	Glutatione	Increase	Decrease
	Tannins	No reproducible effects reported	Increase

Heatwave risk

Grapevines tolerate temperatures of up to 40°C fairly well, but their physiology is severely disrupted once temperatures exceed 45°C (Gouot *et al.*, 2019b). Climate change is causing more frequent heatwaves, which can occur throughout the growing season. This problem is already obvious in California, heatwaves shortly before harvest (in September) can cause severe berry wilting, considerably damaging both the crop yield and quality. The risk of scalding rises when bunches are directly exposed to sunlight in extreme heat (box I-3-1).

Effects of increased water deficit

The intensity of water deficit determines its effect on grapevine physiology. Up to a certain point, water deficit can reduce yield but improve wine quality.

Photosynthesis

In grapevine, as in other plant species, water deficit leads to a decrease in photosynthesis (figure I-3-5A) through relatively well-known mechanisms (Maroco *et al.*, 2002).

Even under fairly severe deficit, it is mainly the closing of the pores on the leaf surface, the stomata, that causes the drop in photosynthesis (Flexas *et al.*, 1998; Gambetta *et al.*, 2020). These pores must be open to allow diffusion of CO_2 from the air into the leaf, where it can be used by enzymes involved in photosynthesis. When these pores close, the plant inevitably loses water, losses which are aggravated by a dry atmosphere. To avoid a fatal level of dehydration, plants have developed a complex mechanism that regulates water losses by reducing the stomatal opening (Tombesi *et al.*, 2015). This response, which is particularly effective in grapevines (Hochberg *et al.*, 2017; Charrier *et al.*, 2018), results both from a decline in leaf turgidity, which allows a rapid and reversible response, and from

Box I-3-1. Lessons to be learned from a severe heatwave in France

On 28 June 2019, a sudden, intense and unprecedented heatwave hit the vineyards of the Gard and Hérault regions in south-eastern France, severely damaging the vines. An analysis of aggravating and mitigating factors was undertaken.

Reports from 1,500 affected winegrowers were collected by the local extension services, supplemented by data supplied by Sudvinbio, a wine trade association, and two insurance companies, Groupama and Pacifica. With the support of the Departmental Directorates of the Territories and Sea (DDTM) of Hérault, information from over 2,000 situations was compiled and analysed by scientists from the Vine & Wine Sciences research group in Montpellier.

Declared yield losses averaged around 33%, in line with insurance company appraisals. More reports of berry sunburn were observed on the west sides of rows running north to south, and more often on exposed bunches near the ground than on the leaves, with the ends of shoots sometimes unaffected.

The intensity of the damage was primarily linked to the air temperature, which peaked at 46.2°C in the mid-afternoon, but other factors also played a major role, with noticeable differences observed between neighbouring fields. Neither soil water deficit, which was moderate at the time of the heatwave, nor irrigation appeared to be the dominant explanatory factors for the varying degrees of damage. However, this variability appeared to correlate with local variations in the evaporative demand of the air (which more than doubled when the air temperature rose from 35°C to 45°C), suggesting that the plants were unable to compensate for the water evaporating from the leaves or fruit. More unexpectedly, the wind, although relatively light, had a mitigating effect (cooling the plants despite the heat), especially when it exceeded 10 km/h. On the same day, varietal differences in sensitivity to the heatwave were noted in Montpellier on almost 300 varieties planted in pots. Winegrowers reported issues with Carignan grapes more than with other varieties. However, this variety was often treated with sulfur, which worsened the reported losses.

Further investigations revealed other factors suspected of exacerbating the damage (shallow soils, bare borders to the west or obstacles to the east of fields) or mitigating it (soils with high water holding capacity, vineyards located near water bodies).

At the end of the study, case-by-case recommendations were suggested. When forecasts predict temperatures exceeding 43°C and winds under 10 km/h, sulfur treatments and leaf removal are not recommended, while inter-row operations are recommended to modify the albedo and curb evaporation-related water losses. Longer-term recommendations have been suggested for the most vulnerable situations.*

* More information can be found at https://herault.chambre-agriculture.fr/actualites/detail-de-lactualite/actualites/note-du-service-viticulture-suite-a-la-canicule-du-vendredi-28-juin-2019/ (Accessed 07/10/2024)

the activation of biochemical processes involving abscisic acid, a key plant hormone that plays a part in adaptations to water stress (Tardieu and Simonneau, 1998). These various mechanisms could explain variety-specific differences in behaviour (Prieto *et al.*, 2010; Coupel-Ledru *et al.*, 2017), with the rootstock also playing a role (Peccoux *et al.*, 2018).

Finally, the decrease in photosynthesis follows stomatal closure quite closely when the soil dries out (Medrano *et al.*, 2003; Pellegrino *et al.*, 2006; Lovisolo *et al.*, 2010). A rise in vapour pressure deficit (a measure of atmospheric dryness) amplifies this response (Prieto *et al.*, 2010), which remains reversible under a wide range of conditions (Flexas *et al.*, 2009). Only severe and sudden dehydration, or moderate but prolonged dehydration, can damage photosynthetic metabolism (Flexas *et al.*, 2009). Water losses are regulated by increasing stomatal and hydraulic resistance to sap flow, but this can weaken the plant by affecting carbon assimilation.

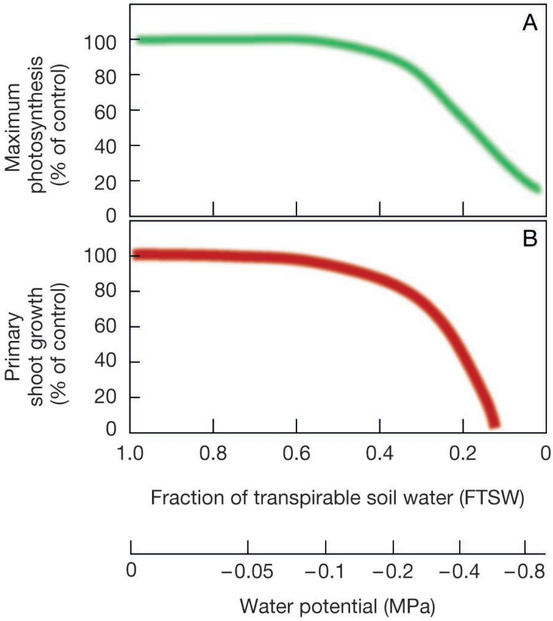

Figure I-3-5. Responses of maximum photosynthesis (not limited by light) (A) and primary shoot growth (B) to soil dryness measured by the fraction of transpirable soil water (FTSW) or predawn leaf water potential. Based on Pellegrino *et al.* (2006); Baeza *et al.* (2007).

The grapevine vascular system is moderately drought resistant, making it vulnerable when the water tension in the xylem falls to −2 to −3 MPa (megapascal), which is likely to lead to embolism (Lamarque *et al.*, 2023). To prevent this phenomenon, grapevines have a deep root system that provides access to water and limits xylem tension as well as very early stomatal control. Long-term observations in the winegrowing regions of Napa Valley, California (between 2010 and 2016, on Cabernet Sauvignon, Cabernet Franc, Syrah and Merlot), and Bordeaux, France (between 2003 and 2016, on Cabernet Franc and Merlot), showed that the vines never reached their fatal water potential thresholds during seasonal droughts (Charrier *et al.*, 2018). However, during very severe droughts, embolism was observed in peripheral organs such as petioles, leading to premature leaf drop and reduced transpiration (Charrier *et al.*, 2016; Charrier *et al.*, 2018).

If droughts occur repeatedly, the resulting decline in carbon assimilation (lower gas exchange) can be detrimental to the long-term vineyard survival.

Shoot growth

Shoot growth (particularly growth of secondary branches) is rapidly affected by moderate levels of water stress, well before photosynthesis is significantly disrupted (Pellegrino *et al.*, 2006; Figure I-3-5B). Shoot growth cessation promotes accumulation of photosynthesis products in the form of reserves, as has been shown in trees (McDowell, 2011). The plant can draw from these reserves to mitigate the impact of a prolonged deficit (Rogiers *et al.*, 2011). As a result, lower growth observed in a given year often does not translate to yield losses.

Shoot growth cessation is the earliest symptom of water deficit. The phenomenon results both from the drop in turgidity required for cell growth and from changes in the activity of various proteins that are involved in slowing down cell divisions or cell wall expansion (Cramer *et al.*, 2013). The slowdown in shoot growth limits leaf area, and when added to the effect of stomatal closure, it further reduces photosynthesis.

Grape production

Like heatwaves, water deficit can affect all yield components. As early as the year before a given year's harvest, if water deficit occurs when the inflorescence starts to form in the latent buds, fertility and yield can be reduced (Guilpart *et al.*, 2014), although this effect is not always noticed (Chacón-Vozmediano *et al.*, 2020).

If severe water deficit develops before or around fruit set, with a water potential near −0.7 MPa, berry number can also be reduced (Wenter *et al.*, 2018). Cell multiplication processes, which are very active during flowering and pollination, are particularly sensitive to water deficit (Lebon *et al.*, 2008). Too low a level of carbon reserves following a temperature increase can also lead to greater abscission during fruit set (Greer and Weston, 2010; Pagay and Collins, 2017). At the end of the ripening period, severe water deficits can cause the berries to wilt, further shrinking their volume (Deloire *et al.*, 2021).

Finally, although all yield components are affected by water deficit, smaller berry size is often the main factor that causes lower yields (figure I-3-6B; Ojeda *et al.*, 2001; Triolo *et al.*, 2018 and 2019). Yield loss is also greater when water deficits set in before veraison (Pellegrino *et al.*, 2014), because berry growth is less sensitive to water deficit during the ripening period. Moreover, yield losses worsen after successive dry years (Chacón-Vozmediano *et al.*, 2020). Major variations are also observed between varieties (Mirás-Avalos and Intrigliolo, 2017).

Grape primary metabolite composition

Water deficit affects photosynthesis, shoot growth and berry size. The balance between these three effects explains the rather complex effect on the composition of primary metabolites (sugars and organic acids) in grapes.

Sugars

The impaired photosynthesis caused by water deficit limits sugar production, which can have repercussions on berry composition. This effect is easily observed in the sugar accumulation dynamics in the grapes – known as sugar loading – when the amount of sugar accumulated (sugar content) is expressed in milligrams/berry. Figure I-3-6A shows the berry sugar loading for three parcels of Merlot and Cabernet Franc grapes, grown in different soils in the Saint-Émilion region in 2005 – the driest year ever observed in the Bordeaux winegrowing area. Sugar loading was highly limited in gravelly soil (low water availability) compared with clay soil (moderately high water availability) and sandy waterlogged soil (no limitation on water supply due to a water table within reach of the roots). Changes in berry weight were also highly dependent on water availability: berries remained small in gravelly soil, of medium size in clay soil and larger in sandy soil with a water table accessible to the roots (figure I-3-6B). If sugar accumulation in the berry is expressed in terms of concentration (g/L), the effect of water deficit on berry weight almost entirely offsets the effect on sugar loading, with the result that sugar levels remain surprisingly similar (figure I-3-6C). The natural conclusion is that grapevines have a substantial capacity to regulate grape sugar concentration. It should be noted that the sugar concentrations are slightly higher in clay soil with moderate water constraints, where the sugar loading had little impact compared to a non-limiting water supply, but with an already reduced berry weight.

Ripening can be disrupted under conditions of very high water stress. In extreme cases, water stress can provoke stuck ripening. Such situations are fairly rare and are usually confined to parcels of young vines with root systems that are not yet fully developed. Usually, ripening is delayed and may be stunted under unlimited water supply, not because of a reduced photosynthesis (which is maximum in this situation), but because of competition between ripening, berry growth and shoot growth (Van Leeuwen *et al.*, 2022b).

Organic acids

The total acidity of grapes produced by vines under water deficit is lower due to a lower malic acid content (Van Leeuwen *et al.*, 2009). Ramos *et al.* (2020) also found higher acidity levels in Rioja grapes in rainy years. This may be a direct effect of water deficit on malic acid metabolism, or possibly an indirect effect. Vines under water deficit are often less vigorous because shoots stop growing earlier, which creates a warmer microclimate in the area in the bunch zone, favouring the breakdown of malic acid.

Grape secondary metabolite composition

The higher quality of wine produced from vines grown under water deficit is explained by increased concentrations of secondary metabolites in grapes.

Phenolic compounds

Various studies have shown that water deficit has a positive effect on the synthesis of phenolic compounds, particularly anthocyanins (Ojeda *et al.*, 2002; Van Leeuwen *et al.*, 2009). Castellarin *et al.* (2007b) reported an increase of 37% to 57% in anthocyanin content in bunches from vines grown under water deficit compared with irrigated controls, and described the genomic regulatory mechanisms that explain these differences.

Aromas

Water deficit is generally favourable to aroma expression in wines, as it reduces green aromas (especially from IBMP) and increases monoterpenes, C_{13}-norisoprenoids and volatile thiols (provided the deficit is moderate; table I-3-1). Water deficit is also known

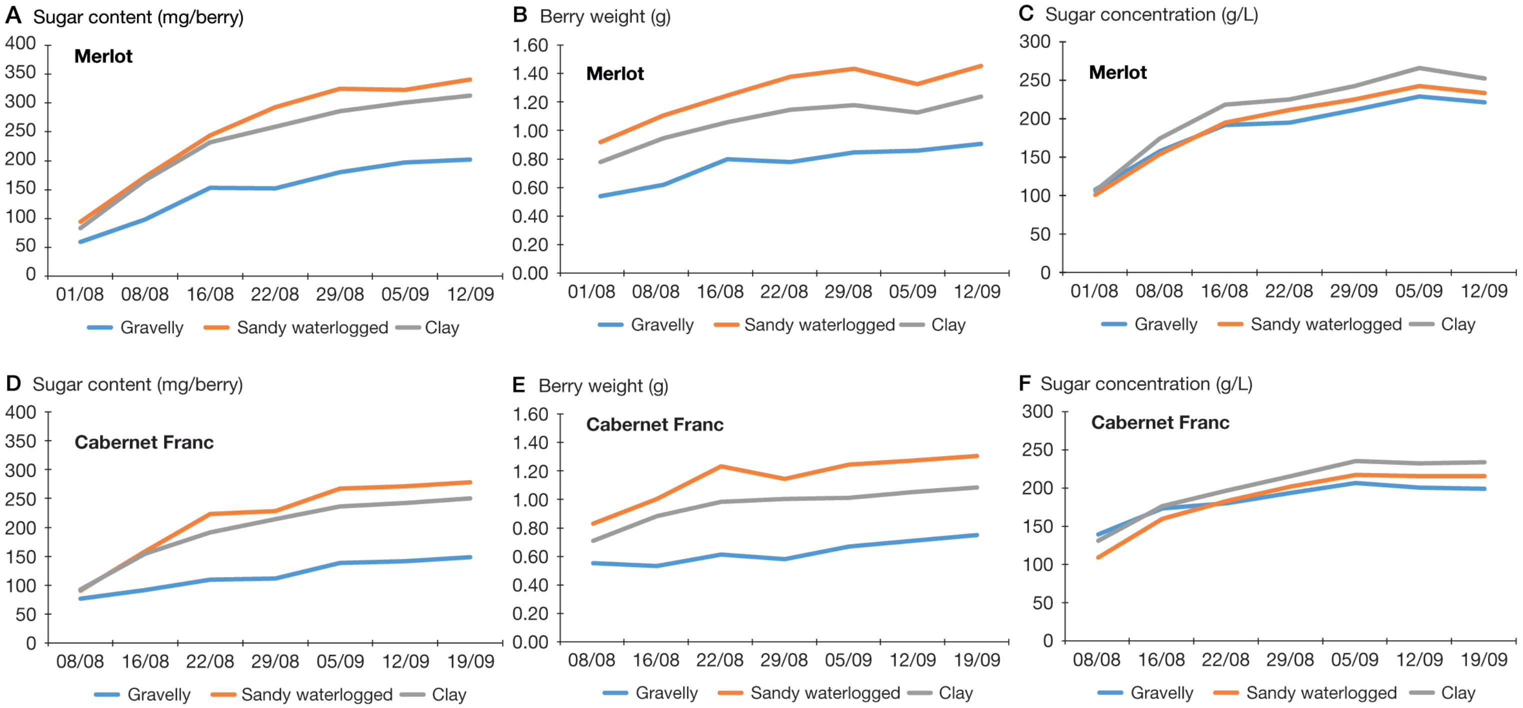

Figure I-3-6. Ripening dynamics in three parcels with different soil types in 2005 in Saint-Émilion (France), for Merlot and Cabernet Franc.

Gravelly: soil with very low water availability; **clay:** soil with moderate water availability; **sandy waterlogged:** water table within reach of the roots, unlimited water supply. Sugar loading expressed in milligrams per berry for Merlot (A) and Cabernet Franc (D); changes in berry weight (B and E) and sugar accumulation expressed in grams per litre (C and F).

to reduce rotundone levels and influence typicity linked to peppery aromas (Geffroy *et al.*, 2016). When vines experience a water deficit during ripening, the wines produced develop a more appealing ageing bouquet (Picard *et al.*, 2017; Le Menn *et al.*, 2019). However, severe water stress can cause atypical ageing linked to the development of aminoacetophenone in Riesling wines (Hühn *et al.*, 1999) and can lead to cooked fruit aromas in red wines, probably linked to an indirect effect of berry shrivel.

The effect of water deficit on secondary metabolites is discussed in more detail in the next chapter.

Wine quality

Because water deficit has a positive effect on phenolic compounds and most of the aromatic families associated with wine quality, it enhances wine quality (particularly for red wine). Estimating the water deficit faced by the vines during the ripening period can be done using water balance modelling. The output is the fraction of transpirable soil water (FTSW). This indicator reflects how dry the soil is: the lower the value, the greater the water deficit experienced by the vines. It is striking to note that in nearly all the very good years for wine quality, the FTSW was low during the ripening period. This is the case in Bordeaux (figure I-3-7A) as well as in Châteauneuf-du-Pape, an even more surprising finding, because this wine-producing area is located in a dry climate (figure I-3-7B).

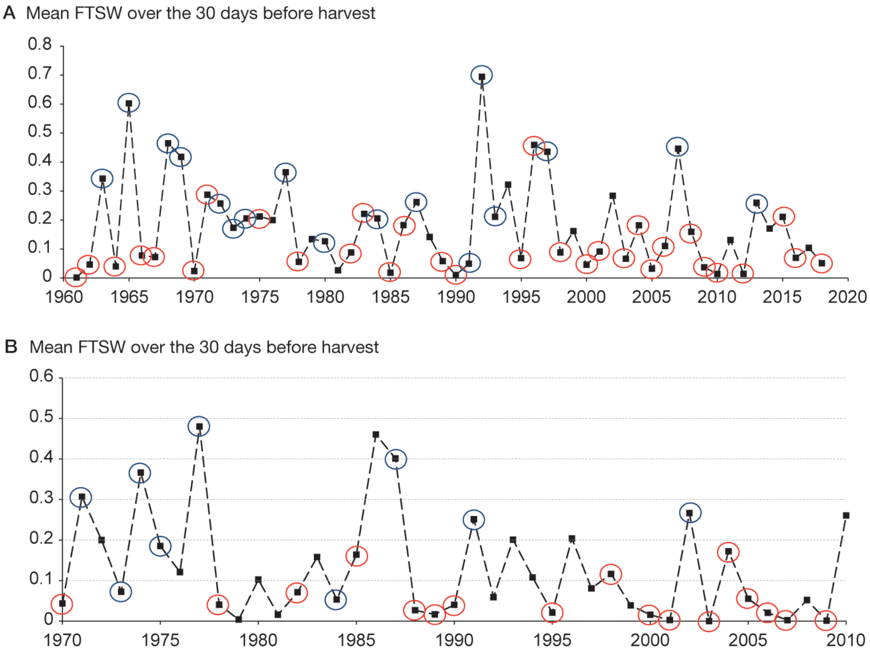

Figure I-3-7. Level of water deficit estimated by modelling the fraction of transpirable soil water (FTSW) during the last 30 days before harvest for a parcel with a density of 5,000 vines/ha and total transpirable soil water (TTSW) of 200 mm.

The lower the FTSW value, the drier the year. Good to very good vintages are circled in red, and average to poor years in blue. (A) Bordeaux region 1961–2018 (climate data from INRAE–Villenave-d'Ornon and Météo-France–Mérignac stations) and (B) Châteauneuf-du-Pape 1970–2010 (climate data from INRAE–Avignon station).

The effects of climate change on grapevine pests and diseases

Winegrowing faces major challenges when it comes to reducing pesticide use while preserving yield and berry quality in the face of climate change. Combating pests and diseases is a critical aspect to take into account when adapting vineyards to climate change. As we saw above, changes in the seasonal dynamics of temperature and precipitation affect yields through effects on grapevine physiology and phenology. These climate-related changes have an indirect impact on pests and diseases as well as on the vine's ability to resist them. Climate variability also influences the scale of epidemics through its direct effect on life cycles of pathogens, their growth rate and their aggressiveness, which in turn affects disease development in vineyards.

An exhaustive review of the literature on the subject

Between 1988 and 2020, some 155 scientific articles described the impact of different climate variables on grapevine pests and diseases. These articles studied 462 individual interactions between grapevines, a climate parameter and a pathogen or pest, using either modelling approaches or experiments and observations in the laboratory, greenhouse or vineyard (Po, 2020). Among the climate parameters, temperature was studied most often (47% of interactions), followed by rainfall (17%), humidity (14%) and drought (8%). Pathogens (66% of interactions, mainly downy mildew, powdery mildew and trunk pathogens) were studied more than pests (20% of interactions, mainly European grapevine moths, leafhoppers and mealy bugs).

Of all the interactions studied, 30% showed that changing climate parameters created more favourable conditions for grapevine pests (and therefore more potential damage to vines), while 20% created unfavourable conditions for pests (less potential damage). For example, higher rainfall could lead to greater damage from downy mildew while higher temperatures could lower European grapevine moth reproduction. That said, half of the interactions showed variable effects or no significant effect of changed climate parameters on pests, depending on the experimental conditions, the years or the traits of the organisms studied.

This quantitative literature review (Po, 2020) concluded that not enough research has been done on the impact of climate change on grapevine pests and diseases, since only a small number of studies have directly addressed this issue (155 in 30 years). In these articles, the wide variety of experimental conditions, traits studied and climate parameters tested makes it impossible to obtain precise predictions of how damage to grapevines will be modified as a result of climate change. It is important to take into account 1) the phenological differences between grapevine and the pests and diseases that affect it and 2) the often complex interactions between the physiological response of grapevine and that of pests and diseases to the environment. Understanding the issues involving grapevine pests and their response to climate change will depend on these considerations (Caffarra *et al.*, 2012).

Next we will discuss the specific impacts of temperature and water on the way grapevines and their pests and diseases interact.

Effect of temperature

The effects of temperature variations on grapevine pests and diseases will depend on the optimum temperature for the different phases of their developmental cycles, especially the propagation and infection phases (Togashi, 1949; Bebber *et al.*, 2020). Theoretically, a rise in temperature would initially lead to more pathogenic fungal species present in the northern hemisphere (Chaloner *et al.*, 2021), since warmer conditions will be more favourable to the development of many fungal and oomycete species. However, if the optimum temperatures for pathogens and pests are exceeded, a decline in these organisms would be expected. For example, several fungal species that cause grapevine trunk diseases have wider or narrower optimal temperature ranges, with maximum mycelial growth temperatures ranging from 30°C to 40°C, suggesting different responses to global warming (Songy *et al.*, 2019). Increasing temperatures therefore have a major impact on the biology, phenology and range of grapevine pests and their natural enemies (Stavrinides and Mills, 2011; Reineke and Thiéry, 2016).

Effect of water deficit

Drought can have a direct impact on the pests and diseases present in vineyards, or an indirect one via the vine's physiological status. These impacts will also depend on pathogen ecology: biotrophic, necrotrophic and vascular pathogens respond in different ways to water stress (Oliva *et al.*, 2014). For example, the infection efficiency of biotrophic and necrotrophic pathogens, such as the pathogens that cause powdery mildew and grey rot, should decrease when the water potential and stomatal conductance of the

Box I-3-2. Vineyards and fires

The combined effects of high temperatures and drought increase the risk of fire. Successive IPCC reports have warned that this threat increases with each temperature increment (IPCC, 2021). In recent decades, there have been multiple major fires around the world. Many of the world's winegrowing regions, including Australia, Chile, California and France, are located in sensitive areas and have had to face this scourge.

However, vineyards can slow the progression of fires and act as firebreaks (Ascoli *et al.*, 2021; Thach, 2018). For example, during fires in the vineyards of the Pyrénées-Orientales region in France in 2023, little damage was done to vines in production, although drip irrigation systems were destroyed. Fallow vineyards and some poorly tended fields, however, increased the risk of damage due to bushes and dry grasses that easily caught fire.

In parcels that are burned, the damage to vines can vary. The most affected vines may show lower growth, starch content in the perennial parts and bud fertility in the year after the fire. Recovery can take one or two growing seasons (Collins *et al.*, 2022). The most significant risk is that of having "smoke taint" in wines made from grapes exposed to smoke, which can lower the potential quality (Krstic *et al.*, 2015). These undesirable flavours are due to volatile phenols that are produced not only during the combustion of biomass and deposited on the grapes, but also by the grapes themselves, which metabolize the volatile phenols via the shikimic acid and phenylpropanoid pathways. Green grapes are particularly exposed to this second process, as the volatile phenols are rapidly degraded, but their glycosylated metabolites are stored in the berries for longer (Jiang *et al.*, 2021).

vine decrease with water stress (Guilpart *et al.*, 2017). Conversely, it has been shown that drought could increase damage caused by grape phylloxera (Savi *et al.*, 2019) and Pierce's disease (Costello *et al.*, 2017; Del Cid *et al.*, 2018). Grapevine trunk pathogens (Botryosphaeriaceae) inoculated on rooted cuttings also cause greater necrosis under water stress (Van Niekerk *et al.*, 2011; Galarneau *et al.*, 2019). However, under conditions of natural infection, drought has also been shown to inhibit the development of leaf symptoms associated with esca disease (Bortolami *et al.*, 2021). Since vascular pathologies and drought both have an impact on water transport in the plant, strong interactions, whether synergetic or antagonistic, are expected depending on the timing and intensity (Oliva *et al.*, 2014; McDowell *et al.*, 2008).

The literature review by Po (2020) showed that, overall, there have been relatively few experimental studies on the interaction between grapevine biotic agents and water deficit (particularly for powdery mildew and downy mildew, the two diseases that account for most phytosanitary treatments). Additionally, few studies have actually quantified the physiological status of the vine during experiments by measuring water potential or gas exchange, which is essential for studying vine–pest/disease interactions in the context of climate change.

Conclusion

Climate has a very strong effect on the phenology, physiology and biotic environment of grapevines. The climate parameters with the greatest impact are temperature and the factors that influence water status (precipitation and reference evaporation or ET_0). Just as temperature and the level of water deficit are being altered by climate change, so the behaviour of vines has changed significantly over the last few decades and will continue to do so. The most dramatic changes include an advance of several weeks in phenological stages, rising sugar levels in grapes (which subsequently increase wine alcohol content), and modified levels of secondary metabolites. These average trends do not imply that vineyards should immediately be moved to different production areas. Adaptive measures can help to mitigate the effects of climate change, as grapevines are generally well equipped to cope with them. However, beyond the average trends, the increase in the number and intensity of droughts combined with peaks of extreme heat are cause for concern. As well as increased the risk of fire (box I-3-2), these conditions can have irreversible and cumulative effects that are not yet fully understood, and which could threaten the long-term survival of grapevines.

CHAPTER 4

IMPACTS ON WINE QUALITY

Cécile Thibon, Aurélie Roland, Philippe Darriet, Pierre-Louis Teissedre, Michael Jourdes and Alexandre Pons

Introduction

The varietal aroma of wine comes from a wide range of volatile odorants. The composition of these odorants strongly influences the perception of tones specific to a grape variety, which are in turn related to the terroir where that variety was grown. Varietal aroma depends on the chemical composition of the grapes at the time of harvest. Grapes contain both volatile odour compounds and a wide range of aroma precursors, which are released during the winemaking and maturation processes by chemical, biochemical or microbial means. These volatile compounds are often found in trace amounts (micrograms per litre of wine) or even ultratrace amounts (nanograms per litre). However, volatile compounds often have high odour intensities and therefore can contribute to the particular odour that a wine may develop when young or during bottle ageing.[25]

When assessing the impact of local climate change on white and red wine quality, we have to consider the concept of fruit ripeness. This parameter determines the wine composition and, indirectly, its sensory balance and stability over time.

Grape ripening is a dynamic process that begins at veraison and continues until harvest. During this process, berry composition changes considerably, both in terms of primary metabolites (sugars, organic acids) and secondary metabolites (phenolic compounds, aroma precursors and aromas, antioxidant compounds and the relative abundance of reactive oxygen species).

Harvest quality and the resulting wine are highly dependent on the harvest date and, by extension, the determination of optimum ripeness. As Ribéreau-Gayon and Peynaud (1961) quite rightly remarked in *Traité d'œnologie*, "It is difficult to rigorously define the state of grape ripeness. Everyone knows what a ripe grape is, but ripeness is not an absolute characteristic. There is no definitive, easily identifiable physiological state, but rather degrees of ripeness." Grape ripeness varies from year to year depending on how the grape varieties and terroirs respond to the climate constraints during the growing season, such as temperature, water status and sunlight exposure. Ultimately, vineyard managers draw from their knowledge of vine health, climate and aesthetic factors when making choices to achieve the desired harvest quality.

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[25] This specific property of odorants is known as the sensory detection threshold, defined as the concentration above which 50% of a panel of tasters can distinguish between a wine containing the compound from one without it.

The impact of climate change on wine aroma

Wine aroma is partly due to volatile compounds, which can be classified according to their chemical family, origin (grape metabolism, pre-fermentation biochemical reactions, fermentation metabolism, post-fermentation reactions) or olfactory contribution (Ribéreau-Gayon *et al.*, 2017; Van Leeuwen *et al.*, 2022a).

Some of the volatile compounds in grapes end up directly in the wine without undergoing further changes. This is true for methoxypyrazines, which impart green aromas in wine (Allen *et al.*, 1991), (−)-rotundone with peppery nuances (Wood *et al.*, 2008), and certain terpenes (Ribéreau-Gayon *et al.*, 2017). In most cases, volatile compounds are formed from non-volatile, non-odorous precursors found in grapes, including glycosylated forms (terpenes, C13-norisoprenoid derivatives), *S*-conjugated forms for varietal thiol precursors or complex lipid derivatives for lactones. These volatile compounds are released into the wine through biochemical or chemical mechanisms during the winemaking and maturation stages.

Odourless precursors in grape berries represent the aromatic potential. Levels of these precursors tend to increase during the ripening phase according to kinetics specific to each precursor with a few exceptions. These accumulation dynamics can be directly impacted by the ecophysiological condition of the vine. Although there are still gaps in our knowledge, studies have provided new insights by characterizing genes and studying their expression in relation to the accumulation in grapes of compounds such as monoterpenes, alkyl-methoxypyrazines and lactones (Duchêne *et al.*, 2009; Sasaki *et al.*, 2016).

Harvest date can affect the various sensory attributes of the grape berry, such as the expression of vegetal characters and fruity aromas. These sensory attributes are particularly prominent in grape varieties such as Merlot or Cabernet Sauvignon and depend on the growing and ripening conditions. When harvested early, red grapes and the wines produced from them are marked by vegetal scents reminiscent of ivy. When fully matured, these wines have a complex blend of aromas of blackcurrant, blackberry and strawberry. Conversely, when picked late and overripe, Merlot grapes and, to a lesser extent, Cabernet Sauvignon grapes (as well as the wines produced from them) tend to have notes of dried fruit, such as prune and fig, which are characteristic of oxidative wines.

Grape varieties with "simple" flavours (i.e. varieties that are not very fragrant when harvested at maturity) often develop cooked fruit nuances when harvested late and overripe or even withered. Once again, it is difficult to define overripeness from a physiological point of view, as it depends on the grape variety. However, recent research has identified odorant molecules associated with these aromatic nuances, including furaneol and homofuraneol, which smell like caramel and overripe strawberries; γ-nonalactone, which is reminiscent of coconut and overripe peaches; 3-methyl-2,4-nonanedione (MND), which smells like prune pits; and massoia lactone and 1,5-octadien-3-one, which have an odour of dried figs. These compounds are all directly or indirectly involved in the cooked fruit aroma of overripe grapes and the red wines made from them (Allamy *et al.*, 2018). The levels of these compounds can be measured to assess the early onset of aromatic development in grapes due to a change in fruit physiology during a period of stress (heat, water or sunlight). For example, studies on MND in Merlot grapes, a variety that is fairly sensitive to overripening and withering, showed that an MND level of over 100 ng/L in the must corresponds to a very advanced level of grape ripeness, with an odour of cooked fruit. When the berries wither, the levels of another family of compounds, lactones (γ-nonalactone, massoia lactone), increase sharply. Figure I-4-1 illustrates, for example, the impact of the vintage on theγ-nonalactone content in wines. The very hot summer in 2003 caused many Merlot berries to wither, which permanently altered the wine composition.

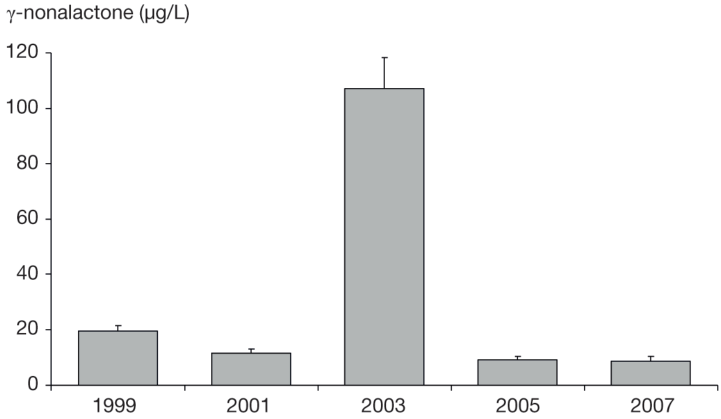


Figure I-4-1. Average γ-nonalactone levels found in wines from different vintages of the same Lalande-de-Pomerol crus (analyses carried out in 2010, n = 2).

Effect of temperature and sunlight exposure

While increased temperatures can have an obvious impact on plant physiology and metabolism (respiration, evapotranspiration, etc.), a change in sunlight exposure can also have a major impact. Sunlight on the berries acts as a source of heat. It also triggers multiple photochemical reactions that can induce oxidative stress, which affects both the redox balance and the primary and secondary metabolism of berries. Pronounced changes in temperature and sunlight levels during berry ripening can cause varying degrees of damage. The incidence and severity of damage depend on the complex interaction of these factors, as well as the biochemical, physiological and morphological state of the berries, all of which depend on the phenological stage and the grape variety. Symptoms range from the appearance of spots on the skin to total berry necrosis and desiccation, known as sun scald or sunburn. In these extreme cases, the yield and quality of the wine produced from these berries will be severely affected.

Over the last few decades, many authors have sought to characterize the impact of temperature and sunlight on the sensory attributes of wines (Bonada and Sadras, 2015; Cataldo *et al.*, 2021; Drappier *et al.*, 2019; Pons *et al.*, 2017). For example, an increase in temperature and sunlight during the development of grapes from the Carmenet family (e.g. Cabernet Franc, Cabernet Sauvignon, Carménère) substantially reduces the levels of 3-alkyl-2-methoxypyrazines with green nuances (Allen *et al.*, 1991; Falcão *et al.*, 2007). When it comes to C13-norisoprenoid derivatives, levels of 1,1,6-trimethyl-1,2-dihydronaphthalene (TND), which produces kerosene aromas in Riesling wines, rise substantially after the removal of the first leaves during veraison as this operation increases grape sun exposure (Schüttler *et al.*, 2015). Other studies had similar findings for final levels of terpenes and their glycosylated forms (including linalool, citronellol, nerol and geraniol) and C13-norisoprenoids (TDN, 3-oxo-α-ionol, β-ionone and β-damascenone), while higher UV radiation appears to have a negative impact on the amount of fatty acid ethyl esters in Pinot Noir wine (Friedel *et al.*, 2016; Sasaki *et al.*, 2016).

Some authors have sought to determine the impact of a moderate temperature rise (around +0.5°C) on the sensory attributes of wines. Using a system developed to modify the temperature around the grape bunches from fruit set to harvest (Sadras and Soar, 2009), researchers conducted an experiment in a plot of Cabernet Sauvignon and Sauvignon Blanc in the Bordeaux region. Sensory analysis of the white and red wines from this trial did not reveal any significant effect of temperature between the experimental and control treatments. Researchers looked specifically at the volatile thiols of these grape varieties, which are varietal markers that produce fruity notes in wine. While no significant differences were observed in 3-sulfanylhexan-1-ol (3SH) concentrations, levels of 4-methyl-4-sulfanylpentan-2-one (4MSP, with odours of boxwood) (Darriet *et al.*, 1995) were significantly lower in the wines produced from the heated grapes (Darriet *et al.*, 2019). However, temperature had a strong effect on the accumulation kinetics of non-volatile *S*-conjugate precursors (Peyrot des Gachons *et al.*, 2002; Roland *et al.*, 2011) in grapes. At harvest, heated grapes had levels of S-3-(hexanal)-glutathione (glut-3SH-Al; Thibon *et al.*, 2016) that were up to 70% lower than levels in control grapes (Wu *et al.*, 2019).

In addition to temperature, sunlight can affect grape ripeness. Sunlight was found to promote lactone and aldehyde formation in red grapes under controlled conditions, most likely through oxidation mechanisms (Allamy *et al.*, 2018). These compounds are markers of cooked fruit aromas.

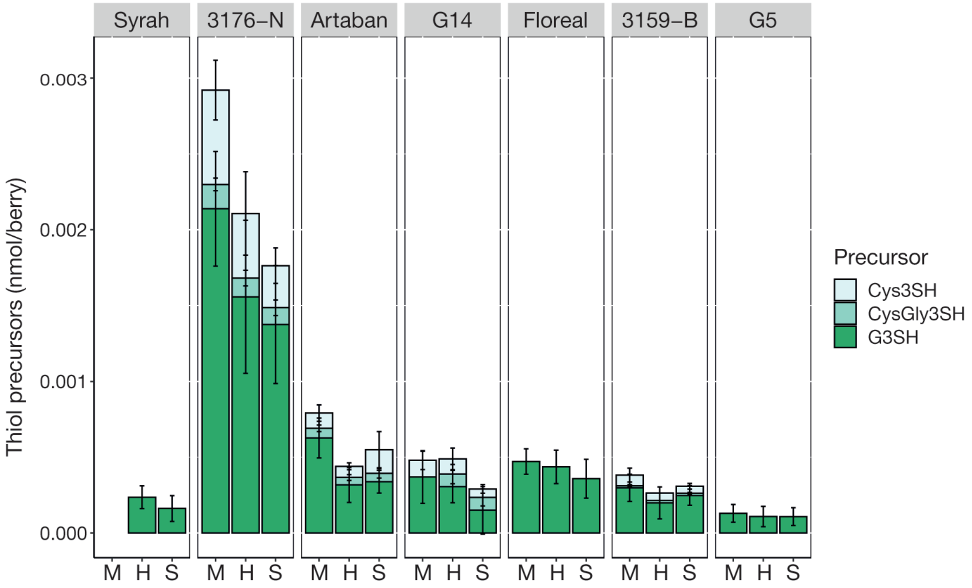
Effect of water status

Climate change is having a major impact on rainfall cycles. If droughts become more frequent, they will be a serious concern for winegrowing in the future, and especially in south-eastern France. When vines grow under a water deficit, the ensuing changes in vine metabolism and the aromatic profile of wines are all the more problematic as yields also fall (Van Leeuwen *et al.*, 2009; Zufferey *et al.*, 2017). Maintaining wine quality standards hinges on understanding the consequences of a water deficit or a change in water status on grape quality.

Recent research on Sauvignon Blanc grapes has demonstrated the beneficial effect of a moderate water regime on thiol precursor levels. Conversely, severe water deficits affect grape ripening and lead to lower levels of thiol precursors in grapes (Cataldo *et al.*, 2021; Peyrot des Gachons *et al.*, 2005) and volatile thiols in wines (Schüttler *et al.*, 2013). Studies have also shown that a slight water deficit induced an increase in the levels of the glutathione and cysteine precursors of 3SH in the leaves of Koshu, Chardonnay and Merlot vines (Kobayashi *et al.*, 2011). However, the response to water deficit appears to depend on the grape variety and the region in question. In Valais (Switzerland), levels of the cysteine precursor of 3-sulfanylhexan-1-ol (Cys3SH) were not affected by the water status of the Petite Arvine grape variety, regardless of vintage (Zufferey *et al.*, 2020).

Recent studies have characterized the accumulation of metabolites and other solutes by accurately determining the stage of grape development (Alem *et al.*, 2021; Bigard *et al.*, 2018) and by characterizing the physiological state of the vines (Wilhelm de Almeida *et al.*, 2023). For the 2021 vintage, the content of thiol precursors was compared to different degrees of water stress, from moderate (−0.4 to −0.6 MPa) to strong (−0.6 to −0.8 MPa) and severe (−0.8 to −1.2 MPa).

Genotype remains the main cause of variation in thiol precursor levels. When levels were expressed as average concentrations, no significant effect of water stress was observed on the panel of genotypes studied. However, a quantitative assessment at the berry level (nmol/berry) did show a significant decrease in thiol precursor levels under water stress (figure I-4-2). This result shows that when there is a water shortage, vines limit both water intake and the accumulation of thiol precursors in the same proportions. It is interesting to note that the genotypes that were richest in thiol precursors were the most affected by water stress under the experimental conditions studied.



M = Moderate water stress, H = High water stress, S = Severe water stress

Figure I-4-2. Effect of water stress on thiol precursors for different genotypes. Levels are expressed in nmol/berry for a specific physiological stage (end of phloem loading). Source: Wilhelm de Almeida *et al.* (2023).

A severe water deficit can also increase the formation of volatile compounds, such as monoterpenes in Riesling wines (Schüttler *et al.*, 2013). Other studies confirmed the differential evolution of varietal aroma compounds as a function of vine water status by measuring carbon isotope discrimination (δ^{13} C values) in must made from mature grapes (Van Leeuwen *et al.*, 2010). As such, (−)-rotundone has been detected at a higher level in wines made from grapes with a lower water deficit (i.e. musts with higher δ^{13} C values). Similarly, for Muscat wines, Giordano *et al.* (2013) reported higher levels of free linalool and geraniol (+70%) in irrigated plants than in plants grown under a drought regime. Meanwhile, De Royer Dupré *et al.* (2014) observed increased dimethyl sulfide potential (a compound that enhances fruit notes in red wines) in Grenache grapes with lower $\delta^{13}C$ values (higher water deficit). Researchers have also used carbon isotope discrimination of ethanol to correlate by extrapolation the perception of a qualitative ageing bouquet in fine Bordeaux wines with a higher water deficit (Picard *et al.*, 2017).

The cumulative effects of higher temperatures and lower water levels in the context of climate change are likely to lead to changes in the primary and secondary metabolism of grapes, with the risk of sun scald, berry scorching/desiccation and possibly even a failure to ripen. An increase in night-time temperatures could also amplify the effects of water deficit on the biosynthesis of volatile compounds and precursors in grapes. Many of these studies took only the grape variety and not the rootstock into account. However, a grape variety's response to low-water and high-temperature conditions can, of course, produce contrasting results depending on the rootstock. Rootstock greatly affects vegetative growth, yield and phenology, and thus it also affects berry quality. Berdeja *et al.* (2014) and Treeby *et al.* (1998) demonstrated a significant impact of the rootstock on the amino acid content of grapes at harvest. Research in Australia on 3-isobutyl-2-methoxypyrazine (IBMP) also confirmed that the rootstock (in this case, 140 Ruggeri compared to Börner) affected the levels of this compound in Shiraz grapes (Sanders *et al.*, 2023).

The impact of climate change on phenolic compounds in wine

Climate change, especially rising temperatures, are affecting more than just the sugars, organic acids and aroma compounds in wine. These changes are also causing higher concentrations of phenolic compounds (anthocyanins and tannins), which play a key role in the quality and character of red wines. Although phenolic compounds are found in smaller amounts in white wines, they contribute to the quality and stability of those wines as well. Members of this large family of molecules are derived from the secondary metabolism of plants. Phenolic compounds affect red wine quality and typicity through their sensory attributes, such as colour, astringency and bitterness as well as through their combinations during ageing (McRae *et al.*, 2013; Teissedre and Jourdes, 2013). Anthocyanins are red pigments found mainly in grape skins and sometimes in the pulp. They are a type of flavonoid and are differentiated by their degree of B-ring hydroxylation and methylation and the esterified group on the sugar. The colour of red wines – the first attribute that consumers judge – depends on the accumulation of anthocyanins during grape ripening, their extraction during winemaking and wine ageing, and how they change during wine ageing due to interactions they produce with condensed tannins and other compounds (Ribéreau-Gayon *et al.*, 2017).

Condensed tannins are polymers of flavanols that differ in their asymmetric centres and the number of galloyl substituents esterified in the C3 position. The main flavanols are catechin, epicatechin, gallocatechin, epigallocatechin and epicatechin-3-*O*-gallate. These monomeric units are linked together by C4→C8 or C4→C6 carbon–carbon type B interflavan bonds (Teissedre and Jourdes, 2013). Condensed tannins in the grape skin differ from those in the seeds in that they contain prodelphinidins, have a higher average degree of polymerization and contain smaller amounts of galloyl derivatives (Chira *et al.*, 2009; Prieur *et al.*, 1994). At the sensory level, a positive correlation has been observed between the degree of polymerization, galloylation percentage (%G) and astringency of wines (Chira *et al.*, 2009), while monomers have been described as affecting bitterness. Although flavanols, condensed tannins and anthocyanins derive from the flavonoid biosynthesis pathway, differences in how they are regulated mean that environmental conditions impact them differently.

Effect of temperature and sunlight exposure

Many studies have looked at how temperature and sunlight affect phenolic compounds (Cohen *et al.*, 2008), but experimental parameters and artefacts can limit interpretation of the results. As such, these results are not necessarily comparable with what happens in the field. Temperature increases, whether through direct heating, incident radiation or higher air temperatures, have been shown to increase plant metabolism and thus the accumulation of associated metabolites (Downey *et al.*, 2006). However, at high temperatures, many metabolic processes slow or completely stop. In grapevine, it is generally accepted that the temperature at which phenolic compounds begin to accumulate is around 30°C to 35°C (Coombe, 1987). Numerous studies carried out from veraison to harvest have shown that these temperatures lead to a drop in anthocyanin concentrations in grape berries (Drappier *et al.*, 2019; Tarara *et al.*, 2008).

A study comparing the kinetics of anthocyanin accumulation in Merlot berries in a vineyard between the east side (receiving morning sun) and the west side (exposed to afternoon sun and therefore warmer temperatures) of the rows showed that grape berries on the cooler east side had higher levels of anthocyanins (Spayd *et al.*, 2002). These findings were consistent with those of Bergqvist *et al.* (2001) on Cabernet Sauvignon and Grenache grapes. To separate the effects of sunlight and temperature, Spayd *et al.* (2002) artificially cooled the berries exposed on the west side and heated the least exposed fruit on the east side. Cooling the fruit exposed on the west side led to an increase in anthocyanin levels, while heating the less-exposed fruit reduced anthocyanin levels. These results show that temperature impacts anthocyanin accumulation more than sunlight exposure. Downey *et al.* (2006) confirmed these findings on Shiraz grapes using a lightproof box that allowed other microclimate parameters (e.g. humidity or temperature) to remain unaffected. Another study found that, in addition to lower anthocyanin concentrations, the proportion of trihydroxylated anthocyanins (delphinidin, petunidin and malvidin) and *p*-coumaroylglucosides was higher under a high-temperature treatment compared with under a control treatment (Haselgrove *et al.*, 2000).

Various studies have also investigated the impact of increased temperature and sunlight exposure on the accumulation and composition of condensed tannins in grape seeds and skins. These studies found that a moderate temperature increase around grape bunches (+1°C to +3°C) from fruit set to harvest did not affect the condensed tannin content of grape seeds and skins at harvest (Carbonell-Bejerano *et al.*, 2013; Wu *et al.*, 2019). However, studies showed higher concentrations of condensed tannins under both high-temperature and high-sunlight (exposed fruit) conditions compared with under low-temperature and low-sunlight (shaded) conditions at veraison and mid-veraison (Cohen *et al.*, 2008; Wu *et al.*, 2019). Condensed tannin levels in the grape berry typically peak at veraison and then fall until harvest. This decrease is generally thought to be due to a decline in extractable tannins (Amrani Joutei *et al.*, 1994; Downey *et al.*, 2003). This lower extractability, which occurs regardless of the growing conditions, was more marked for berries that had been subjected to higher temperatures or sunlight exposure, which resulted in concentrations close to those at harvest (Cohen *et al.*, 2008; Wu *et al.*, 2019).

Effect of water status

Water deficit during the berry growth phase when phenolic compounds (anthocyanins and tannins) are biosynthesized generally leads to a higher concentration of these compounds. One reason for this is the smaller berry volume, which alters the proportion of seeds and skins in relation to the pulp, and therefore the balance during the maceration and extraction stages of winemaking (Castellarin *et al.*, 2007b). However, accumulation of phenolic compounds is primarily linked to an increase in the enzymatic activity of the flavonoid biosynthesis pathway. In addition to an overall increase in phenolic compounds, several studies have also shown an impact of water status on phenolic compound composition. The proportion of trihydroxylated anthocyanins (delphinidin, petunidin, malvidin) increases under water deficit as does the degree of tannin polymerization in the skins (Cáceres-Mella *et al.*, 2017; Castellarin *et al.*, 2007a), but these changes in phenolic compound composition depend on the variety (Zarrouk *et al.*, 2015). Conversely, a significant water deficit before veraison reduces anthocyanin and tannin levels in the berry due to lower biosynthetic activity (Ojeda *et al.*, 2002). However, higher temperatures have a greater influence on phenolic compounds than moderate water stress at mid-veraison (Bonada *et al.*, 2013).

Conclusion

Recent advances in winegrowing practices and quality wine production have been driven by the development of research-supported techniques to determine grape ripening and knowledge of the molecular mechanisms associated with ripening. Climate change is creating a new paradigm in the world of wine. It is no longer enough to simply let the fruit ripen, winegrowers now must control the level of ripeness to ensure the long-term production of quality wine that reflects the local terroir. This is why knowledge of the impact of temperature, water regimes and sunlight exposure on berry and wine composition and quality is so important.

In this chapter, we described the impact of climate change on the aroma and phenolic compounds in white and red wines. Climate change can adversely impact plant primary and secondary metabolism. Additional research is needed to characterize the direct consequences and extent of these changes, not only on the aromatic potential of the grapes, but also on the quality and sensory perception of the wines.

The issues related to climate change also raise the question of how to adapt to maintain wine typicity. Once again, knowledge of the molecules responsible for the sensory attributes of grapes and wines is essential to select varieties, clones and rootstocks that are more tolerant of extreme climatic conditions.

CHAPTER 5

ADAPTING TO CLIMATE CHANGE USING GRAPEVINE IDEOTYPES

Éric Duchêne, Élisa Marguerit and Aude Coupel-Ledru

Introduction

In the face of climate change, the viticulture and wine industry can exploit various adaptation strategies, including those involving shifts in space (growing regions), time and wine profiles. We define a successful strategy as one that can ensure current regional wine volumes and quality in the future. This objective can be achieved by adopting combined technical approaches, such as a mixture of modified viticultural practices (chapters I-6 and I-7), cellar practices (chapter I-8) and, potentially, vineyard location (chapter I-9), to take advantage of fine-scale variability (Bonnefoy *et al.*, 2013). In this chapter, we explore how grapevine genetics can be incorporated into adaptation strategies, and we ask, what would the ideal variety look like and how could it be created?

Earlier chapters (I-3 and I-4) examined how climate change may functionally affect grapevines. In brief, we first expect to see phenological shifts. Budburst should occur earlier, which means buds will be at greater risk of experiencing spring frosts, particularly in vineyards in the northern hemisphere (Sgubin *et al.*, 2018). There will be delays in the onset of ripening: veraison will occur during the hotter periods of the summer. The result will be less acidic wines with different secondary metabolite profiles. One of the greatest concerns is increased water stress, which may negatively affect productivity in the current and subsequent growing season. Little is known about the cumulative effects of repeated droughts because it is difficult to carry out field monitoring over several growing cycles.

Furthermore, the IPCC (2021) has predicted that rising temperatures will be accompanied by an increased frequency of extreme climatic events, such as heatwaves (which will burn plant tissues), heavy precipitation and hail storms. While qualitative in nature, this information must nevertheless be used to inform adaptation efforts.

Several approaches can be taken to adapt grapevines. First, it is possible to utilize existing clone collections to effectively identify new clones of a given variety that produce grapes with higher acidity or lower sugar content. One advantage of clonal selection is that new clones can be grown in current viticultural regions, including in European regions with protected designation of origin status, without requiring any regulatory changes. The downside is that the genetic variability represented in clone collections may be too limited and thus insufficient for crafting satisfactory responses to long-term expectations around quality and yield. Second, adaptation strategies can centre on the rootstock, such that drought tolerance is increased without altering wine typicity. Finally, it is possible to change the scion varieties used. Taking all three approaches together may be the best way to ensure the successful adaptation of grapevines.

How genetic variability can be leveraged for adaptation

The use of different or even new genotypes for scions and rootstocks is a powerful technique for adaptation. It should be possible to identify triads of scions, rootstocks and training systems that will yield commercial-quality wine in many winegrowing regions. That said, there is no way to guarantee that future production volumes will remain the same. We need to identify the characteristics to develop tomorrow's varieties.

Modifying grapevine growth stages to produce high-quality wines

With veraison shifting to occur under excessively hot temperatures, it could be possible to adapt by using clones or varieties that ripen later than those currently employed. Intraspecific genetic variability in veraison timing has been well described (Parker *et al.*, 2013), and current models can predict future phenological patterns using climate data (e.g. Fila *et al.*, 2014). Researchers have identified numerous genomic regions (i.e. quantitative trait loci, or QTLs) that are related to phenology (Costantini *et al.*, 2008; Duchêne *et al.*, 2012a; Gomès *et al.*, 2021). This information can be used to model how different genotypes might respond if grown in different viticultural regions under future climatic conditions. But our research shows that, even if late-ripening varieties are used, the grapes of the future will likely never experience the cool ripening temperatures of the present (Duchêne *et al.*, 2010). Indeed, there is an ever-widening gap between the autumn's cooler ripening temperatures, which are occurring later and later, and the onset of ripening, which is shifting towards the hottest part of the summer. We may be able to expand the window of late ripening by drawing on new genetic resources, including interspecific variability within the genus *Vitis*. However, it may be short sighted to overemphasize phenology. In the quest for promising genotypes, equal consideration should be given to maintaining grape characteristics, such as colour and acidity, under hotter conditions.

Genotypes with greater water use efficiency

In the near future, summers are expected to become drier, and potential evapotranspiration will climb. Thus, crop water use efficiency (WUE) is a key trait to consider during adaptation efforts. There are many ways to define how well water stress is tolerated (for a review, see Gambetta *et al.*, 2020). From a winegrower's perspective, WUE is the amount of water needed to produce one kilogram of ripe grapes. Numerous researchers have compared how different grapevine genotypes respond to water restrictions, which has given rise to potential classification systems (Gaudillère *et al.*, 2002; Tomás *et al.*, 2014). However, we currently have an incomplete understanding of the degree to which traits related to water stress tolerance are genetically determined. The main challenge is identifying which traits to study, a choice that must be guided by empirical knowledge of how well certain varieties and rootstocks handle drought (see boxes I-5-1, I-5-2, I-5-3). One system classifies cultivars as isohydric or anisohydric depending on their water relations strategy under conditions of water stress. Over the course of a given day, isohydric cultivars are able to maintain high leaf water potential, while anisohydric cultivars will display a significant drop in leaf water potential. The genetic basis for this trait was studied using a QTL approach applied to 186 genotypes (figure I-5-1) produced by a reciprocal cross between Syrah and Grenache cultivars (Coupel-Ledru *et al.*, 2014).

Box I-5-1. VitAdapt: adapting to climate change by optimally employing *Vitis vinifera* diversity

Vineyards can better adapt to climate change by exploiting grapevine diversity and, more specifically, the bountiful number of existing grape varieties. To capitalize on these resources, we need to know how different varieties respond to climatic variables such as temperature and soil moisture. VitAdapt, launched in Bordeaux in 2009, was the ideal project for gathering these data. On an experimental plot, VitAdapt grew and phenotyped 52 grape varieties (31 red and 21 white), including standards of reference for Bordeaux grapes and varieties of wide-ranging origins (i.e. France, Spain, Italy, Greece, Portugal, Bulgaria and Georgia). To study variety-specific responses and control for soil-related variability, 5 blocks of 10 rootstocks of each variety were planted randomly within the plot. The same rootstock and training system was used for all the plants.

The project gathered more than 10 years of monitoring data, which established a clear outline of the timing of budburst, flowering and veraison for the 52 grape varieties. These observations revealed that early- and late-ripening varieties could differ by more than 30 days in their timing, depending on vintage and phenological stage. Starting mid-veraison, weekly samples of grapes were collected. The intent was to study ripening dynamics, which were found to greatly differ. The data were used to group grape varieties according to how early they ripened, as well as by ripening speed and final sugar content. It seems probable that grape varieties that are late to mature or slow to ripen and that accumulate reasonable amounts of sugar will produce well-balanced wines under warmer climatic conditions.

VitAdapt also examined how different varieties of different vintages responded to drought conditions, findings that revealed how water stress was handled at the plant level. Data from 2022 were of particular interest in this context. Grape varieties could be classified according to their degree of defoliation, a trait that could act as a reliable proxy for drought tolerance.

Additionally, the project also considered the importance of other variables, such as plant vigour, production capacity and resistance to certain pathogens, as well as the quality and typicity of wines obtained via microvinification.

VitAdapt generated a database with over 10 years of data characterizing the traits of numerous grape varieties. Using a long-term experimental approach, the project was able to describe the diverse reactions of grape varieties to a particular set of soil, climatic, growing and winemaking conditions. This work will continue – more experimental plots will be established under other pedoclimatic conditions. The long-term data they generate will yield further information about variety-specific responses to other agricultural and oenological factors, making it possible to analyse genotype-by-environment interactions in the context of climate change.

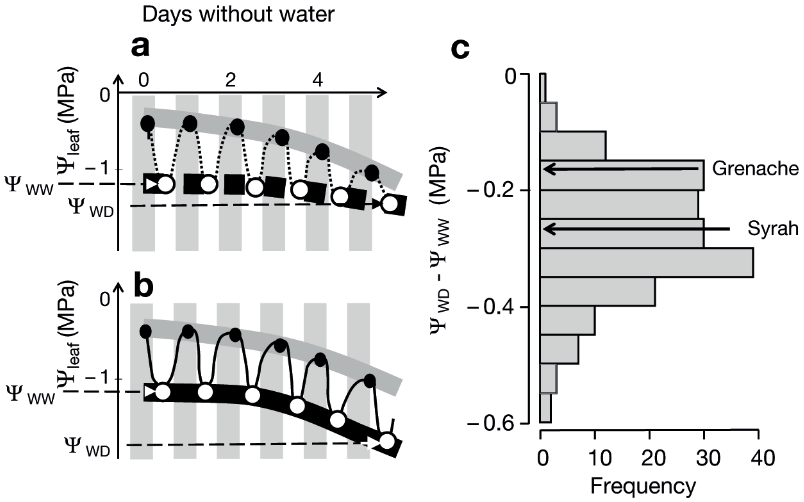


Figure I-5-1. Schematic representation of differences in leaf water potential (Ψleaf) between (a) isohydric and (b) anisohydric plants in response to soil drying and (c) the range of iso- to anisohydric patterns seen in progeny (n = 183 genotypes) from a Syrah × Grenache cross.

The experiment was carried out using potted plants in a greenhouse where the soil water potential (thick grey line and black circles in *a* and *b*) was controlled so as to reach target treatment values for all plants after about five days. Each day, Ψleaf cycles between its predawn values, equal to the soil water potential (black circles in *a* and *b*), and its midday values (white circles in *a* and *b*). A plant's water relations strategy (iso- to anisohydric; depicted in *c*) was the difference in midday Ψleaf between the last day of the water deficit treatment (ΨWD) and the first day of the well-watered treatment (ΨWW). Source: Coupel-Ledru *et al.*, 2014.

This research led to the identification of QTLs for many traits, including the specific transpiration rate, specific hydraulic conductance and minimum midday leaf water potential. The pattern of correlations and collocations among the QTLs for these traits suggests that a plant's water relations strategy (i.e. iso- to anisohydric) may not be governed by a single control mechanism, namely stomatal regulation of transpiration. Instead, stomatal regulation may act in tandem with hydraulic regulation. Crop modelling will be necessary to determine which multilocus combinations of alleles will yield the best responses to low water availability under field conditions (Tardieu, 2003).

Rootstock identity is responsible for dramatic variability in water stress tolerance: ranging from the tolerance associated with 110R to the intolerance associated with Riparia Gloire de Montpellier (Ollat *et al.*, 2015; Serra *et al.*, 2014; see box I-5-2, table I-5-1). Marguerit *et al.* (2012) identified numerous QTLs that are related to the transpiration rate, the δ^{13}C values of leaves, the transpiration efficiency of whole plants and plant water extraction capacity. Their work focused on the responses of Cabernet Sauvignon plants grafted onto rootstocks representing 138 genotypes resulting from a cross between Cabernet Sauvignon × *Vitis riparia* Gloire de Montpellier (figure I-5-2). They discovered that rootstock genotype determined scion transpiration rate and plasticity when facing water stress. Thus, breeding efforts can target rootstocks to improve water stress tolerance.

Box I-5-2. GreffAdapt: speeding up the availability of new rootstocks

Rootstock breeding is a lengthy process. Consequently, in addition to generating new rootstock genotypes, efforts are under way to characterize the rootstocks that already exist worldwide in vineyards and genetic resource collections. This work is a complementary means for rapidly expanding the range of rootstocks available to winegrowers. GreffAdapt is an experimental vineyard that was planted in Bordeaux in 2015 to conduct a detailed study of the drought tolerance and plant vigour displayed by grapevines created using 55 rootstocks (table I-5-1). These rootstocks were combined with five scions (Cabernet Sauvignon clone 169, Grenache clone 362, Pinot Noir clone 113, Syrah clone 524, Ugni Blanc clone 481), which were chosen to increase scion-level genetic diversity while also representing varieties from France's main viticultural regions. With its 275 combinations of rootstocks and scions, GreffAdapt is the only experimental plot of its kind in the world. GreffAdapt aims to identify rootstocks that confer traits of interest, with the ultimate objectives of enlarging the range of rootstocks approved for use in France and of adding new varieties to the French catalogue.

Table I-5-1. List of rootstocks studied at GreffAdapt.

Rootstocks registered in the French catalogue		Rootstocks used in other countries	
101-14MGt 110R 1103P 140Ru 1447P 161-49C 1616C 197-17Cl 216-3Cl 3309C 333EM 34EM 4010Cl 41B 420A 44-53M	99R BC2 Fercal Gravesac 125AA 5BB Nemadex A.B. RSB1 Riparia Gloire de Montpellier Rupestris du Lot SO4 5C 8B Vialla	1045P 106-8 MGt 125-1 MGt 157-11C 225Ru 57R 775P 779P Binova Börner Dog Ridge Evex 13-3 Evex 13-5 Freedom Georgikon 28 Georgikon 121	Georgikon 251 Harmony M1 M2 M3 M4 Ramsey Schwarzmann V15

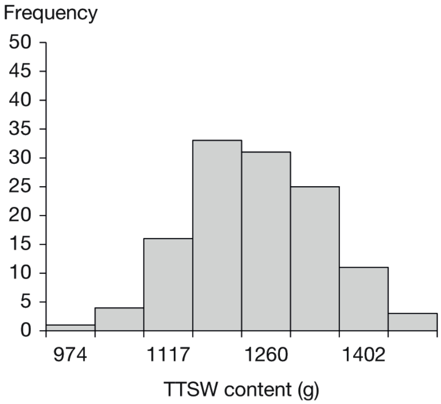


Figure I-5-2. Variability of water extraction capacity (total transpirable soil water, TTSW) in 2008 for progeny from a cross between Cabernet Sauvignon and Riparia Gloire de Montpellier. Source: Marguerit *et al.* (2012).

Genotypes with consistent yields

Yield plays a crucial role in determining whether winemaking operations are sustainable. Productivity must be maintained to ensure the economic sustainability of vineyards. At the same time, the resulting wines must also be of good quality, a reality that is often at odds with high grape loads.

A solid genetic basis, with accompanying variability, exists for potential yields (Fanizza *et al.*, 2005). There is a notable impact of inflorescence number per shoot (Doligez *et al.*, 2010), which likely affects flower number per shoot, although this variable is rarely measured (Zinelabidine *et al.*, 2021). The number of berries per bunch may also vary among genotypes. Zinelabidine *et al.* (2021) and Doligez *et al.* (2013) found that the genetic architecture involved in berry mass may be uninvolved in berry seed number. Although researchers have identified genes (reviewed by Carmona *et al.*, 2008) or QTLs (Doligez *et al.*, 2002; Fanizza *et al.*, 2005) that are linked to several aspects of yield, the underlying functional and genetic mechanisms have yet to be fully characterized (Carmona *et al.*, 2008). At present, there are no yield-related markers among the marker-based tools used during early-stage breeding of scion varieties.

A major goal of adaptation efforts is to maintain reasonable yields under the warmer and drier conditions associated with climate change. Water stress can affect berry size in the current season (Niculcea *et al.*, 2014) as well as the number of inflorescences or flowers per shoot the following season (Guilpart *et al.*, 2014). However, studies looking at interactions between genotype and water stress responses are currently focused on the leaves; the different aspects of yield have yet to be examined. It is important to note that water stress is not the only functional challenge that grapevines will face as a result of climate change. The number of fertile shoots is largely determined by bud number post pruning. However, plants have faced unanticipated spring frosts in recent years, a pattern that is consistent with climate predictions (Sgubin *et al.*, 2018). To adapt, it may be necessary to use varieties that bud later or that can replace lost primary shoots with fertile secondary shoots, a trait known to have a genetic basis with accompanying variability (Cheylus, 2021). Little research has looked into the frost resistance of plants at identical bud development stages (Derreudre *et al.*, 1993; Fuller and Telli, 1999); frost avoidance is mainly tied to budburst timing.

Finally, temperatures around the time of budburst are likely to influence the number of flowers per inflorescence (Petrie and Clingeleffer, 2005; Pouget, 1981) and, consequently, potential yield. To the best of our knowledge, nothing is known about varietal responses in this context either.

Optimizing grape composition consistency

The effects of climate change on grape and wine composition are discussed in detail in chapters I-3 and I-4. Berry sugar content has been found to vary greatly among genotypes, whether comparisons occurred on the same date (Duchêne *et al.*, 2012b) or on the date when sugar contents reached an established value (Costantini *et al.*, 2008). Berry sugar content is also influenced by climatic conditions and water availability during the period between grape veraison and harvest, as well as by the plant fruit-to-leaf ratio.

In the progeny of a Riesling × Gewürztraminer cross, the genetically mediated effects of veraison timing and fruit-to-leaf ratios largely explained sugar concentrations, but there was a small amount of residual genetic variability (Duchêne *et al.*, 2012b). This measurable genetic architecture (Gomès *et al.*, 2021) is related to variability in genome sequences. Researchers have already developed low-sugar grape varieties that produce wines with alcohol contents of no more than 10%–11% (Ojeda *et al.*, 2017), and measurements of individual berries have highlighted the existence of genotypes associated with low levels of sugar accumulation (Bigard *et al.*, 2022). These results are encouraging, even if the underlying genetic determinants remain to be clarified.

When temperatures are high during berry ripening, berry acidity drops rapidly, due to the breakdown of malic acid (Lecourieux *et al.*, 2017). It is assumed that tartaric acid levels per berry remain constant as berries mature (Debolt *et al.*, 2008), which means that final concentrations depend on berry size rather than on temperature. Varieties with elevated tartaric-to-malic acid ratios are better adapted to warmer climatic conditions. As illustrated in figure I-5-3, this ratio is underlain by genetic variability across grapevine genotypes (Duchêne *et al.*, 2014). While the physiological role of potassium in sugar accumulation remains a subject of debate, potassium is known to neutralize acids and can also form potassium bitartrate, an insoluble compound, in the presence of tartaric acid. The ratio of potassium to tartaric acid plays a determinant role in grape pH, a relationship mediated by genetic factors (Duchêne *et al.*, 2020).

To create an ideotype with relatively low sugar concentrations and high acidity, the variety's grapes will need to be low in potassium but high in tartaric acid.

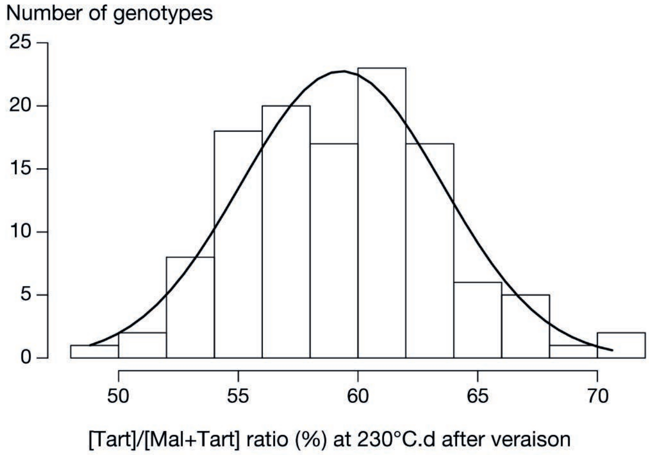


Figure I-5-3. Variability in the relative concentration of tartaric acid (i.e. the concentration of tartaric acid divided by the combined concentration of malic acid and tartaric acid) in progeny from a Riesling × Gewürztraminer cross (n = 120 genotypes). The mean values represented are from 2006 to 2009. Organic acid concentrations for each genotype were measured at a heat sum of 230°C.d after veraison in INRAE's experimental vineyard near Bergheim. Source: Duchêne *et al.* (2014).

Phenolic compounds play a key role in wines: anthocyanins influence berry colour, and condensed tannins affect wine body and astringency. Past studies have shown that anthocyanin concentrations are lower at higher temperatures (Lecourieux *et al.*, 2017; Mori *et al.*, 2007). Experimental research has also shown that, at hotter temperatures, colour loss is less pronounced for Cabernet Sauvignon or Pinot Noir grapes than for Tokay grapes (Kliewer and Torres, 1972). Anthocyanin concentrations are not equally affected by high temperatures: Lecourieux *et al.* (2017) observed greater declines for dihydroxylated anthocyanins than for trihydroxylated anthocyanins, with greater effects seen for delphinidin-3-*O*-glucosides than for malvidin-3-*O*-glucosides. The same study also suggested that higher temperatures had greater impacts on compounds with smaller numbers of methyl groups. Another study (Fournier-Level *et al.*, 2011) observed a relationship between genetic variation along chromosomes 1 and 2 and levels of anthocyanin methylation in progeny from a Syrah × Grenache cross. Taken together, these results indicate that molecular markers could be used to breed varieties capable of maintaining grape colouration at high temperatures. QTLs associated with proanthocyanidin synthesis have also been identified (Carrier *et al.*, 2013; Huang *et al.*, 2014). However, compared to anthocyanins, proanthocyanidins are less sensitive to temperature shifts (Pastore *et al.*, 2017) and are not essential in adaptation efforts.

To date, we know nothing about the variety-specific variation (i.e. plasticity) in aromatic profiles elicited by warmer temperature conditions.

Conclusion

Climate change will significantly alter the environmental conditions experienced by most, if not all, of the world's vineyards. The impacts on wine production will vary depending on region and wine type, but they will not necessarily be all negative: under warmer climatic conditions, producers will be able to harvest ripe grapes every year, and it will become possible to grow grapes in regions that are currently too cool to produce high-quality wines.

The main concerns are that climate change will cause water scarcity, resulting in lower yields, and will lead to the production of unbalanced wines, with high alcohol content and low acidity. The effects on the final concentrations of secondary metabolites (phenolic and aromatic compounds) in wines are less predictable. At present, genetics research has not gone far enough in exploring the oenological characteristics of genotypes that have been evaluated from an agricultural perspective. As of yet, there has been no pyramiding of favourable alleles for the various traits discussed in this chapter.

The first step should be to run tests with existing varieties or clones. Around the world, grapevines are already grown in warm regions, and genetic resource collections contain thousands of cultivars (see box I-5-3). It should be possible to identify scion × rootstock combinations that could be successfully grown in most of the world's current winegrowing regions, outside of those already located at the upper limits of winegrowing temperatures. But the process of identifying agriculturally and oenologically appropriate combinations is no more than an intermediate objective. It will be easier for consumers to accept new grape varieties if wine typicity is preserved. If not, consumers will be forced to accept a shift.

Over the longer term, it will be possible to create new varieties. We are continuously learning more about the genetic basis of traits related to phenology, water use and grape composition; however, the desired specifications for future ideotypes have yet to be established. In other words, breeders do not yet have a clearly defined set of targets. Even when armed with efficient breeding techniques, it generally takes around 10 years to go from an initial seed to a commercially viable variety. Even more time must pass before that variety is grown across large areas. For the first time in the history of variety creation, environmental conditions will change during the period between variety testing and commercial usage. It is thus crucial to reliably predict how genotypes will respond to environmental conditions under climate change. To this end, we need reliable climate models for predicting future environmental conditions as well as crop models that can integrate information about grapevine genetic profiles and environmental responses.

Box I-5-3. Exploiting the Vassal-Montpellier ampelographic collection

The Vassal-Montpellier Grapevine Biological Resource Centre in Marseillan is dedicated to conserving, characterizing and creating value from grapevine genetic resources. Professor Jean Branas at the Montpellier School of Agriculture (since renamed Institut Agro Montpellier) was the force behind the centre's creation in 1949, which began with the ampelographic collection initiated in 1876 by Gustave Foëx and later expanded by Louis Ravaz. For 147 years, the collection has been steadily growing, thanks to donations, exploratory efforts and exchanges overseen by specialists such as Denis Boubals, Pierre Galet, Jean-Michel Boursiquot and, above all, Paul Truel, who was the centre's director from 1954 to 1985.

At present, the centre harbours over 8,000 vine accessions from 55 wine-producing countries. The collection comprises approximately 2,800 grape varieties, 450 wild grapevines, 1,000 interspecific hybrids, 300 rootstocks and 60 species in the family Vitaceae. This ampelographic collection is one of a kind because of its richness and diversity. The objective is to provide various stakeholders in the winemaking industry (e.g. growers, hybrid grapevine breeders, researchers) with these shared resources, whether in the form of cuttings, pollen, seeds or fresh plant material.

Conserved grapevines are systematically characterized based on their morphological features (using descriptors from the International Organisation of Vine and Wine and International Union for the Protection of New Varieties of Plants), phenological features (timing of budburst, flowering, veraison, maturity), agricultural features (vigour, yield components, susceptibility to disease), technical features (berry quality, microvinification properties), health concerns (main viral diseases), genetic information (segregation data, genetic fingerprints, genealogies) and bibliographical information (histories, distributions). Data are shared as part of partnerships. The aim is to identify different varieties and explore their potential to meet the demands of researchers, breeders, viticulture and wine professionals and wine consumers. The centre's documentary collection contains variety descriptions (5,000), a herbarium (14,000 specimens), a specialized library and a photo library (50,000 images). These resources are currently being digitized and uploaded for full online access.

The collection can be deployed as part of climate change adaptation strategies. Examples include:

- supplying varieties for use in grapevine diversification experiments (e.g. employing heirloom or foreign varieties, rootstocks)
- defining working panels representative of global diversity or associated with specific breeding goals, with a view to analysing the genetic determinants of target traits
- exploiting extreme phenotypes to generate new, better-adapted varieties via cross-breeding

With the help of such models, breeders will be able to identify the best combination of alleles to use under a given set of climatic conditions and then launch breeding programmes that deploy the full suite of modern techniques to characterize the genetic profiles of all progeny. Often, for a given target trait, genetic determinants remain unestablished for various genetic backgrounds and sets of progeny; trait variance is explained by not one, but rather several regions explaining a small proportion of the variance in the trait studied. Methods based on genomic selection can help build more comprehensive models, which can fully exploit all available genetic information to make phenotypic predictions. These models will likely play a crucial role in building the genotypes of the future.

Climate change is on course to alter wine production in many regions of the world. Modern grapevine varieties contain a wealth of genetic diversity, which allows wine production to occur across the globe under wide-ranging environmental conditions. Moving forward, this diversity can be employed as is or even expanded through sexual reproduction to generate strategies for adapting to the environmental realities of climate change.

CHAPTER 6

GRAPEVINE TRAINING SYSTEMS AND VINEYARD SOIL MANAGEMENT

Aurélie Metay, Raphaël Métral, Christophe Gaviglio and Cornelis van Leeuwen

There is no single solution for adapting to climate change. When making changes to agricultural systems, solutions must consider different spatial and temporal scales, as well as a combination of short-, medium- and long-term techniques – and that only covers the technical aspects of adaptation. Annual practices can be used to cope with inter-annual climate variability, while longer-term choices can ensure vineyard sustainability (Naulleau *et al.*, 2021). Having covered genetic-based solutions in the previous chapter, we will now turn to vineyard soil management and grapevine training systems. In addition to adaptation, these practices can also mitigate the effects of climate change and support biodiversity.

Soil management challenges due to climate change

As a result of current practices and soil and climate conditions, winegrowing is particularly exposed to issues such as erosion, reduced organic matter content, soil compaction and declining soil biodiversity (Garcia *et al.*, 2018).

Constraints on vineyard soils

The main problems seen in vineyard soils are due to tillage and the infrequent application of organic amendments and plant matter (Salomé *et al.*, 2016). If organic matter is not applied, the soil organic carbon stock, which is key to soil stability, cannot be maintained (Abiven *et al.*, 2009; Agreste, 2020). Grapevines are also often grown on hillsides that are unsuitable for other crops, and weeds are normally controlled to limit competition (Ambiaud, 2012). The row structure of vineyards, combined with winter grapevine dormancy, sometimes leaves much of the soil exposed to weather conditions. Together, these factors make winegrowing one of the land uses most prone to erosion (Le Bissonnais *et al.*, 2004; Raclot *et al.*, 2009). Water run-off and soil erosion also carry away herbicides, which then contaminate water bodies (Louchart *et al.*, 2001).

Soil conservation strategies for winegrowing should focus on land uses and practices that make land less susceptible to erosion (i.e. improving soil aggregation and structure). Inter-row management practices such as planting temporary grass cover have become much more widespread, mainly to reduce the need for herbicides and tillage (Fernández-Mena *et al.*, 2021). When these practices are impossible or insufficient, winegrowers should develop agricultural land along contour lines or plant trees to stop soil erosion on slopes. The aim is to prevent soil being lost to river systems (Follain *et al.*, 2018).

Soil management costs

The cost of managing vineyard soils varies according to different factors, including the winegrowing region, vineyard size and training systems, type of soil, equipment used, tillage and farming techniques. Regular tillage can be a major cost for a vineyard. According to Agreste data (2020), the total average cost of mechanical management of vineyard soils in France is around €427 per hectare. Vineyard soil management costs typically include ploughing, weeding, fertilization, soil amendment and irrigation (Metay *et al.*, 2022). Mechanical tillage between rows and under the vines often costs two to three times more than using herbicides (Constant *et al.*, 2019). Mechanical weeding has a significant impact on vineyard management costs – specifically equipment and fuel (rotary tillers use around 25 L/ha, compared with less than 5 L for rollers) and labour. Mechanical weeding also tends to increase erosion in hillside vineyards (Biddoccu *et al.*, 2017). When mechanized tillage is too difficult or ineffective, workers must do the work by hand, a task that is particularly arduous and costly for the estate in terms of both time and money. A “mixed” management method is often used, where inter-row weeds are mainly managed with mechanical weeding and/or grass cover that gets mown, while in-row weeds are controlled with herbicides – doing without herbicides under the row remains a significant challenge (Metay *et al.*, 2022).

Soil management: adapting to or mitigating climate change

Several vineyard soil management practices can be used to adapt to climate change and its effects on soil and crops. First, farming practices should help the soil hold water, such as permanent plant cover between the vine rows, organic mulch and trees planted in and around vineyards. These practices limit erosion and increase the soil’s water retention capacity, thereby reducing the risk of water stress. However, a very high level of plant cover between rows increases soil water transpiration and may lead to water and nutrient competition (Celette and Gary, 2013). Secondly, irrigation methods need to consider the water requirements of vines, and tools should be used to measure the soil water content to adjust the amount of water applied.

Vineyard soil management can also reduce greenhouse gas emissions by promoting soil carbon storage. For example, maintaining grass cover between rows helps return organic matter to the soil, thereby boosting the carbon sequestered in the soil (Autret *et al.*, 2016). The use of organic soil amendments and compost can also improve soil carbon storage. Other practices, such as reducing nitrogen fertilizer use and optimizing water management, can in turn lower greenhouse gas emissions by limiting the conditions that support denitrification, and thus curb N_2O emissions. Finally, good soil management and less ploughing can promote soil carbon storage at the surface (0–10 cm; Cai *et al.*, 2022) by maintaining organic matter and limiting erosion (figure I-6-1). However, if all the anthropogenic soil horizons are considered down to 60 cm, no change in carbon stock is observed after tillage is stopped (Autret *et al.*, 2020). These practices are discussed in the next section.

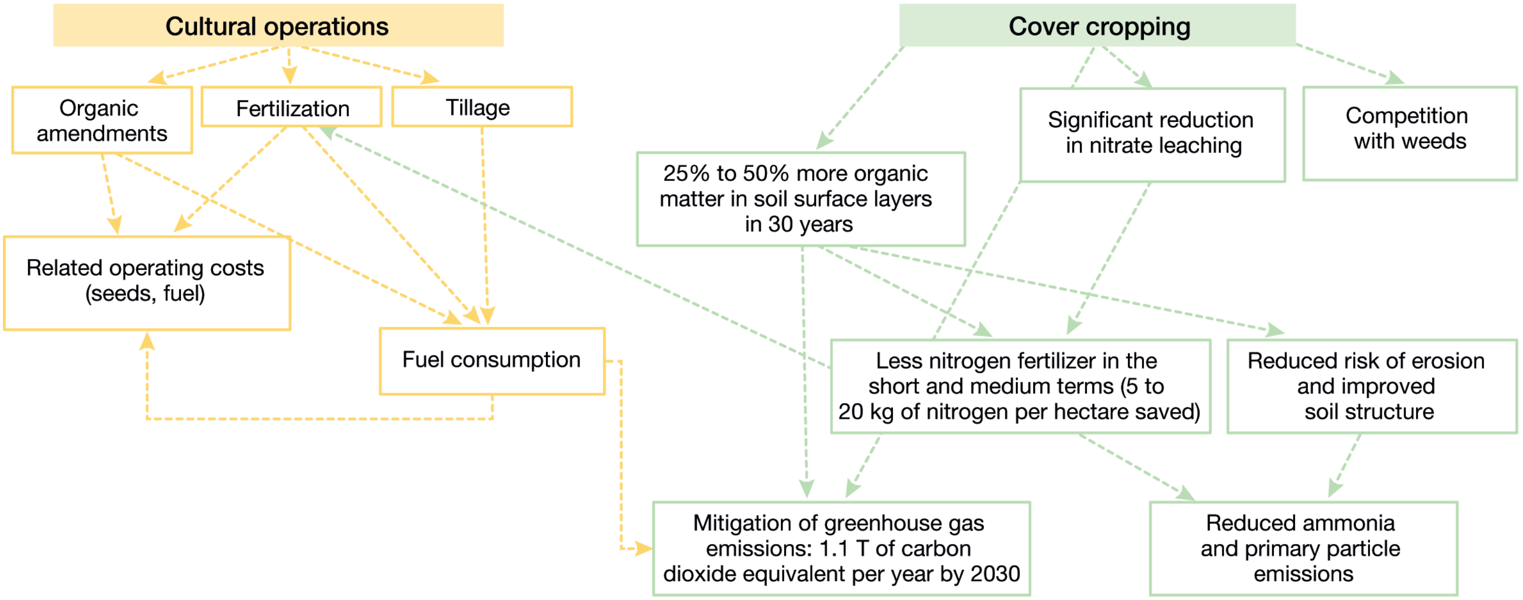


Figure I-6-1. Soil management practices used to adapt to and mitigate climate change. Example of a legume cover crop. Based on ADEME fact sheet no. 5, “*Cultiver des légumineuses pour limiter l’utilisation des intrants de synthèse*” [Planting pulses to limit synthetic input use] https://librairie.ademe.fr/cadic/2918/6-cultiver-des-legumineuses-reference-ademe-8130.pdf (accessed 14/01/2024).

Soil management practices

Mechanical tillage, weed control, fertilization and the use of soil amendments can all be combined to increase grapevine resilience to climate change and limit its environmental impact.

Deep tillage to prepare soil before planting

Grapevines need to be planted in soil with a good structure (porosity) to ensure proper root development and deep soil exploration. The soil morphological features should be assessed before any tillage prior to planting (Gautronneau, 1987) due to the risk of compaction from planting. A preliminary diagnosis is key to choosing the right tools to loosen the soil at depth (e.g. shape and size of tines or blades) as well as deciding the depth at which the soil should be tilled. The primary goal is to break up compacted soil and encourage good root growth. Deep ploughing should be avoided as it mixes up the surface horizons where most biological activity occurs and dilutes organic matter. Soil compaction risk depends both on the characteristics of the soil, such as texture and stoniness, and on the cultivation practices adopted by winegrowers. Vineyard soils, for example, are especially prone to compaction from agricultural equipment being driven back and forth across the fields (Polge de Combret-Champart *et al.*, 2013).

Mechanical and chemical weeding

Restrictions on the use of glyphosate have ushered in radical changes in vineyard weed control, and alternative solutions are being actively sought.

Changes in chemical weed management practices

Under new recommendations issued by the French Agency for Food, Environmental and Occupational Health & Safety (ANSES), winegrowers can now apply glyphosate only twice a year, once at the end of winter and once in the summer (figure I-6-2A). Growers are now limited to 450 g/year/ha, versus 2,160 g/year/ha previously, resulting in major changes in soil management practices that are not necessarily conducive to climate change mitigation. For example, more frequent mechanical weeding practices increase fossil fuel consumption. Conventional in-row weed control strategies involving a combination of systemic, leaf and pre-emergence operations are more difficult to implement. Winegrowers who wish to continue using herbicides under the vines have to implement winter weed control and use specific herbicides to avoid problems in early spring. However, these herbicides are less effective and must be applied more often (three treatments instead of two) to keep the in-row area clear enough to meet production targets. Where perennials are present, only glyphosate is effective, but the smaller 450 g/ha/year dose is not as effective. Treating a narrower area for each application is one way to ensure the treatment remains effective as doing so increases the untreated area of the vineyard. The gradual introduction of mechanical management practices or other alternatives must be considered. According to Agreste, half of all vineyards use a combination of chemical and mechanical weed control methods. Only 20% of vineyards use chemical weed control only, a decrease of 11 percentage points compared to 2016. Meanwhile, all-mechanical methods are on the rise, with 27% of vineyards going this route (up 8 points), including nearly all organic vineyards. To make up for the ban on all chemical herbicides, organic winegrowers make an average of 4.2 mechanical passes (sometimes under and between the rows at the same time), compared with 2.6 in the conventional sector.

Alternatives to chemical weed control exist but are more time-consuming and energy intensive

The most accessible alternative to chemical weed control for winegrowers is mechanical weed control. Various types of equipment on the market can deal with most situations. Mechanical weed control is effective when done well, but it takes four to six times longer than chemical weed control (in the case of rotary tillers; figure I-6-2B). Because mechanical weed control does not provide persistent action, it must be carried out more often at slower speeds to reduce the risk of harming the vine trunks. Equipment can be difficult to

Figure I-6-2. A: application of herbicides under the row; B: rotary tillers mounted on a straddle tractor; C: propane-powered thermal weeder; D: electric weeder prototype. © Christophe Gaviglio, IFV81.

use on hillsides and slopes, and these areas have a real risk of erosion. The root network may also be disturbed. How much fuel is used during tillage depends on whether the equipment is passive or operates with power take-off (PTO), but in any case, fuel use is higher than for chemical weed control. When it comes to taking climate change into account, most chemical-free alternatives are more time-consuming and energy-intensive. As such, there is a need for more far-reaching changes than simply replacing one practice with another to ensure that reduced inputs truly translate to reduced greenhouse gas emissions (such as planting cover crops and using innovative management methods).

Thermal weed control (figure I-6-2C) is effective because the equipment sends heat towards the weeds to apply a thermal shock that causes their cells to burst. But the process is slow and requires repeated passes (five to eight). The time and energy required (greenhouse gases and fuel related to tractor use) means this technique is best reserved for vineyards planted on hillsides or in very shallow soils where tillage is unsuitable. Variations using foam or hot water exist to increase the duration of heat application.

Electric weed control (figure I-6-2D), developed by a company called Zasso, is an interesting alternative method in terms of its mode of action and scope of application. This method works by creating electric arcs between fixed electrodes in the rows and a mobile electrode passing between the trunks. These electric arcs are diffused into the conducting parts of the weeds (leaves, stems and potentially roots), making this method a no-till alternative with a systemic effect. Electrical power is supplied by a PTO-driven generator. This solution could be used in many set-ups, including in vineyards that are difficult to manage with tillage. The soil must be damp to direct the electric arcs produced onto weeds. The challenge is to find a satisfactory working speed to limit time and energy consumption.

Changes to in-row weed control often involve the use of either more herbicides requiring more applications or more energy-intensive practices to replace herbicides. However, with regard to more general soil management, fertilization practices and the use of cover crops, even temporary ones, can boost soil carbon storage (Garcia *et al.*, 2018).

Adjusting nitrogen fertilization

Perennial plants, including grapevines, need nitrogen to grow, even if their needs are lower than for field crops. Unlike field crops, perennials accumulate nitrogen reserves during their growing cycle and store them in their perennial parts for the next cycle. Nitrogen management is important for grape yield and quality targets. Excess nitrogen can reduce quality and promote pests and diseases, while a deficiency can reduce the harvest quality and volume. Nitrogen fertilization increases greenhouse gas emissions. When nitrogen is applied to crops, it can be converted into nitrous oxide (N_2O), a powerful greenhouse gas, through nitrification and denitrification processes in the soil (IPCC, 2019). According to ADEME[26] (2013), nitrogen fertilization accounts for around 20% of agricultural N_2O emissions, or around 1.6 million metric tons of CO_2 equivalent per year. Managing nitrogen is a key factor in limiting greenhouse gas emissions from agriculture. Winegrowers can improve nitrogen use efficiency in plants and minimize nitrogen inputs by adapting the planting material, soil and nitrogen management, and

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[26] https://librairie.ademe.fr/changement-climatique-et-energie/3252-how-can-french-agriculture-contribute-to-reducing-greenhouse-gas-emissions.html (Accessed 08/10/2024).

grapevine management to environmental conditions. Managing nitrogen in vineyards therefore involves striking the right balance between promoting vegetative development (vigour), optimizing grape composition, controlling production costs and limiting pollution (Champagnol, 1984; Chantelot *et al.*, 2004; Spayd *et al.*, 2002).

Valuable amendments

By definition, soil amendments are organic or mineral products added to the soil to improve its properties (e.g. structure, organic matter content, pH) (figure I-6-3). The use of organic soil amendments in winegrowing can effectively increase the level of organic matter in the soil, provided that large quantities are added fairly regularly (every three to five years, at the rate of several metric tons of pomace, compost, etc. per hectare). According to a study conducted in France, applying green waste compost and cattle manure to vineyards increased soil organic matter levels from 0.7% to 1.3% on average after four years of application (Mamy *et al.*, 2014). Applying compost is consistent with more environmentally-friendly agriculture, as composted organic waste can be used as a soil amendment to provide the nutrients needed for food production. A recent study in Spain on the effect of applying three different types of composted organic waste or organic amendments on soil quality and greenhouse gas emissions showed that soil quality was consistently improved from amendment application over the 13 years of the study (Calleja-Cervantes *et al.*, 2015). Although applying soil amendments increased the greenhouse gas emissions from the soil, the organic matter content of the soil rose significantly (at least 35% more in all organic treatments than in the control), and this increase was constant over time. However, the effectiveness of an organic amendment can depend on various factors, including the amendment quality, dose applied, application frequency and soil properties. As such, it is important to adapt application practices to each specific situation to optimize the effects on the level of soil organic matter.

Figure I-6-3. Spreading soil amendments in a vineyard (Languedoc). © Yves Bouisson, INRAE.

Covering the soil

Keeping the soil covered either some or all of the time, using exogenous materials or sown or permanent grass cover, can provide benefits in terms of climate change adaptation and mitigation. Ground cover must be managed depending on each year's climate conditions.

Laying mulch to limit evaporation

Mulch can be used to manage the vineyard establishment phase without herbicides or tillage. Managing the in-row area without using herbicides on young vines is a complex, delicate and time-consuming undertaking that also comes with risks for the plants. Landscape fabric, made from felt or geotextile and pre-cut for planting, can considerably simplify soil management in the row during the first three years of young vines (growth, trunk formation) before they go into production (figure I-6-4A). Mulching is generally expensive, costing around one euro per linear metre for a three-year period. Mulch affects both soil temperature and moisture in the row. It has been shown that after three years, biodegradable mulches are ineffective and must be replaced with another management method. Soil microorganims break down biodegradable mulches and consume nitrogen as they multiply, which can starve the vines of nitrogen. The mulch can also be damaged by wild animals; wild boar, for example, are quick to notice that vineyards have more earthworms.

To use biomass from a cover crop grown between rows as mulch, winegrowers must have the right equipment and a short grass cover in the row, so that the cut mulch can lay flat. A front mount mower is ideal so as to avoid driving over the vegetation before cutting it, and to shred it into small pieces that break down more quickly. An effective winter weed control strategy is key to having thick biomass growth between the row to spread in the row once cut.

Cover crops to improve carbon storage

Planting cover crops between the rows (known as intercropping) is an agroecological practice that can provide a range of ecosystem services (Garcia *et al.*, 2018). Cover cropping protects the soil against erosion, improves ground stability for farm equipment, lowers the need for inputs such as pesticides as well as synthetic fertilizers when legume cover crops are used, and reduces environmental contamination from pollutants (Schreck *et al.*, 2008; Tournebize, 2001). Cover cropping also helps to improve soil fertility by increasing structural stability (Garcia *et al.*, 2019) and surface organic matter by returning clippings to the soil and promoting root humification. Finally, it creates an ecosystem that promotes soil flora and fauna (Coll *et al.*, 2009) (figure I-6-4B). Changes in vineyard soil management practices mainly concern inter-row management.

However, permanent ground cover will likely compete with grapevines for water and soil nitrogen (Gontier and Gaviglio, 2013). This competition can lead to low levels of assimilable nitrogen in the must, which can adversely affect the organoleptic quality of the wine. Competition can even lower yields, making it impossible to meet production targets, which are already likely to decrease as adaptations to climate change are implemented. To offset possible nitrogen deficiencies, early destruction of the plant cover and the use of foliar fertilizers are possible (Gontier and Gaviglio, 2013).

Figure I-6-4. A: felt landscape fabric placed under the row; B: green manure mix (white mustard, broad bean and oat) with high biomass before destruction; C: grass cover under the row cut short; D: spontaneous plant cover managed by mowing and tillage, in a Mediterranean vineyard. © Christophe Gaviglio, INRAE UMR ABSys (A, C); INRAE UMR ABSys (B); Marie-Charlotte Bopp, INRAE UMR ABSys (D).

In 2019, 64% of French vineyards had plant cover between the rows, or 12% more than in 2016 (Agreste, 2020); the plant cover was permanent in 43% of them (either on every other row or on all the rows) and temporary in 19% of them, a share that doubled since 2016. In particular, green manure had been sown between the rows of 4% of vines in 2019 compared with 1% in 2016. Inter-row plant cover is widespread in both organic and conventional vineyards. However, in organic vineyards, the plant cover is often temporary, and it is destroyed mid-season nearly half the time.

In-row plant cover, which is usually spontaneous and temporary, was growing in 12% of vineyards, twice the rate as in 2016 (figure I-6-4C). This type of plant cover is especially prevalent in southern regions (e.g., three quarters of Corsican vineyards, a third of Gaillac vineyards near Toulouse) and is found in almost a quarter of organic vineyards.

Grass cover can be extended in the row as an alternative to weeding. While mechanical weeding between rows is complex, mowing is simpler: winegrowers do not need to worry about depth, for example. That said, working around the vines is still a delicate operation and requires a fairly slow approach. Because weed control is no longer carried out in the rows, winegrowers may have to till the rows or add fertilizer (foliar or buried) instead to avoid excessive competition, which can lower grapevine vigour and yield.

Managing spontaneous vegetation

Planting cover crops in vineyards is not always easy because autumn rainfall can vary at the time of sowing, particularly in Mediterranean areas and due to climate change. To overcome this challenge, managing spontaneous vegetation in vineyards should be viewed as an opportunity to promote more sustainable agricultural practices and thus contribute to the fight against climate change (Bopp *et al.*, 2022; Genty *et al.*, 2023; figure I-6-4D). Spontaneous vegetation in vineyards can impact soil health, especially under climate change. As droughts become more frequent and severe, competition between weeds and grapevines for water and nutrients can intensify. Therefore, agroecological practices are needed to manage weeds effectively (box I-6-1). For example, managing the permanent plant cover between the rows of vines helps limit weed growth and promotes soil biodiversity. Mechanical and thermal weed control techniques can also reduce the need for herbicides and thus curb greenhouse gas emissions. The presence of spontaneous vegetation can also have a beneficial effect on vineyard soils. Some of these plants, such as alfalfa and clover, fix nitrogen in the air, improving soil fertility and quality.

Box I-6-1. Agroecology and climate change

Climate change is a challenge when it comes to ensuring the sustainability of winegrowing systems. Agroecology provides both solutions for adapting to climate change and levers for mitigating its effects. Agroecology relies as much as possible on natural pest control to combine food production with resource conservation and regeneration, namely by promoting better soil health, greater biodiversity and highly diversified agricultural production systems. Transferring and communicating winegrowing practices that support agroecological winegrowing is essential to building an industry that can survive extreme climate hazards.

Winegrowing professionals, and especially winegrowers, have been the first to see the effects of climate change in their vineyards. For this reason, many are already engaged in a rather ambitious agroecological transition. Changes at the vineyard level are already visible.

Researchers have identified various levers by surveying winegrowers managing innovative, highly agroecological vineyards. These levers focus on adapting to and mitigating the effects of climate change (figure I-6-5).

The introduction of shade trees is especially promising for winegrowing systems. In all French winegrowing regions, it is possible to introduce trees in fields. A variety of approaches may be taken, including planting trees for timber or fruit in or near vineyards. Scientific knowledge of tree–vine interactions is still limited (frost and sunburn protection, shade provision, water and nitrogen competition), but research on the subject is very active.

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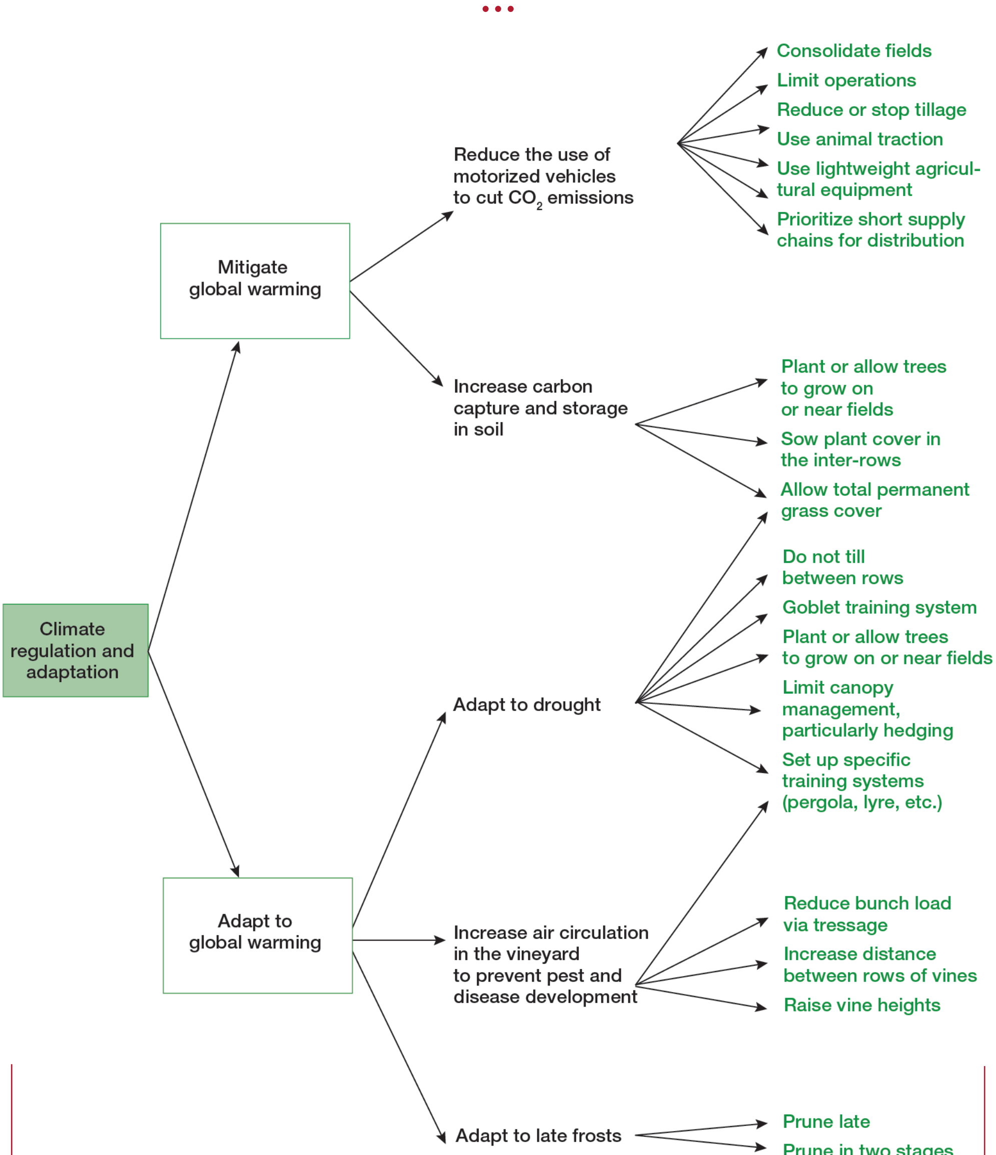

Figure I-6-5. Field-level adaptation and mitigation levers on farms adopting agroecology principles. Source: Merot *et al.* (2023); CPA PPR VITAE project.

Grapevine training systems and climate change

The grapevine training system used in a vineyard determines the spatial layout of the vines (spacing between rows and between vines on the row), the architecture of the perennial parts (trunk and branches) and the canopy configuration. Training systems are an important lever for adapting to climate change. Winegrowers can choose a training system to change the microclimate in the area around the grape bunches and regulate grapevine transpiration to manage water consumption.

Planting densities vary around the world from 1,000 to more than 10,000 vines per hectare, and a wide variety of training systems are used. Winegrowers have developed systems such as pergola, espalier and goblet training. For each location, the winegrower strives for the best compromise between resource management (temperature, water, sunlight and nutrients), yield, harvest quality potential and production costs.

Climate change means that available resources are no longer the same (in most winegrowing regions, temperatures have risen and water resources have fallen), which means training systems will need to be adapted. However, for thousands of years, people have been developing training systems that are resilient to high temperatures and low water availability, such as Mediterranean goblet training. These systems should serve as a knowledge basis when designing new systems (Santesteban, 2020). Even more innovative practices such as agroforestry for winegrowing, pergola training or on-tree vine staking to reduce sun exposure and therefore heat stress (Favor and Udawatta, 2021; Oliva Oller *et al.*, 2022) are currently being developed to adapt wine production to climate change constraints. Implementing these systems raises questions about the design of diversified systems, and managing them will require a precise and dynamic understanding of any competition (for sunlight, water, nutrients) these systems may create.

The effect of vine training on water consumption

Water balance is used to model water availability for grapevines throughout the season (Lebon *et al.*, 2003). Meeting grapevine water needs depends on the soil water reserve at the start of the season (total transpirable soil water, or TTSW) as well as inputs (i.e. rainfall and irrigation, if used). Losses from vine transpiration, plant cover and evaporation from the soil surface must also be taken into account.

The training system impacts water transpiration from the canopy. Sunlight provides the energy for the phase change (from liquid water to water vapour) when transpiration occurs, which increases as the amount of sunlight intercepted by the canopy rises (if soil water is not a limiting factor). Training systems have two features that influence sunlight interception: row spacing and canopy height. These features are factored into the water balance, so it is possible to simulate how the vine's water requirements will be met for different row spacings and canopy heights. Calculating the water balance provides the fraction of transpirable soil water (FTSW), which varies from 0 when the soil is completely dry to 1 when soil moisture is at capacity in the field (maximum amount of water a soil can hold). This type of simulation was carried out for an espalier system with different row spacings (2, 3 and 4 m, with a density of 5,000, 3,333 and 2,500 vines/ha, respectively) based on current and future climate scenarios in two winegrowing regions and at three TTSW levels (100, 200 and 300 mm) (Van Leeuwen *et al.*, 2019b). The study showed that a wider row spacing considerably increased the vine's water availability (FTSW) during the 30 days before harvest, especially in soils with a high water reserve (figure I-6-6). However, in the most extreme scenario (Avignon Côtes du Rhône, soil with a TTSW of 100 mm, future climate scenario), an increase in-row spacing from 2 to 4 m did not increase water reserves at the end of the season.

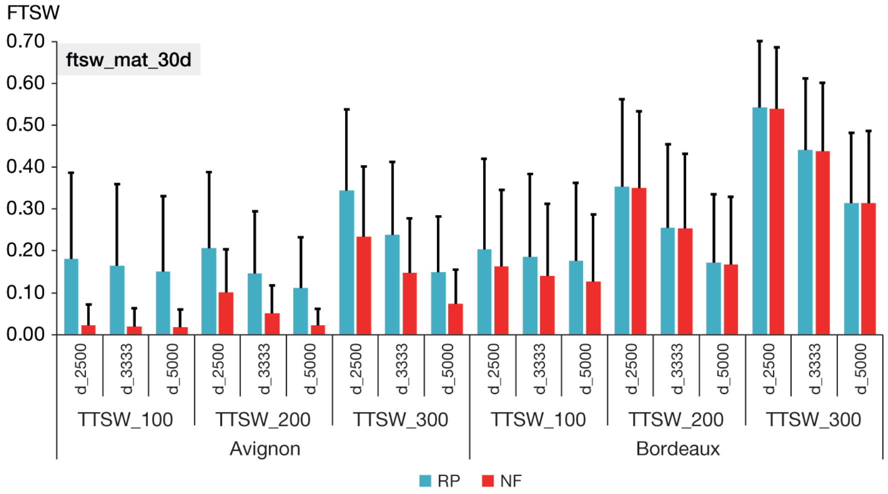

Figure I-6-6. Average fraction of transpirable soil water (FTSW) during the 30 days before harvest for two regions (Bordeaux and Avignon, southern Côtes du Rhône), three TTSW values (100, 200 and 300 mm) and three densities (2,500, 3,333 and 5,000 vines/ha). RP = recent past; NF = near future. Based on Van Leeuwen *et al.* (2019b).

Similarly, keeping the canopy height lower helped reduce water consumption by the vines and maintained greater water availability in the soil at the end of the season. These findings support the use of high-density training systems (associated with a high canopy height to row spacing ratio) in regions where water availability has not typically been a limiting factor (Bordeaux, Champagne, Burgundy), whereas densities have always been lower in the dry regions around the Mediterranean. To adapt to increased water stress in all regions, it is possible in the short term to reduce the hedging height and in the long term to increase the distance between rows. For espalier systems, increasing the spacing between rows reduces transpiration (per unit area of soil) and therefore saves water. It also slightly increases grapevine vigour, which provides shade for the bunches. The lower density of these systems reduces both production costs and yield. This choice is profitable for products with low added value, but the negative effect of the lower yield outweighs the positive effect of lower costs for products with high added value (Van Leeuwen *et al.*, 2019b).

The effect of vine training on the microclimate of vegetation and grapes

Training systems also strongly influence the microclimate of the vegetation and area around the bunches (Smart and Robinson, 1991). Vines planted at low density tend to be more vigorous, particularly in fertile soils or in irrigated fields. Under these conditions, there is a higher proportion of leaves and bunches that are not exposed to the sun, so grapes stay cooler and receive less light (Smart, 1985). In cool climates, this can lead to herbaceous wines (Archer and Strauss, 1985) and a higher risk of fungal diseases, but in hot, very sunny climates, shading the bunches limits the risk of scalding and cooked fruit and oxidized prune aromas in wine (Van Leeuwen *et al.*, 2022a).

The training system also changes the microclimate around the bunches: the bunches are relatively well exposed to the sun in espalier vines (especially at medium and high planting densities), whereas the bunches are more shaded in untrellised, pergola- or goblet-trained vines, which makes these latter three types more suited to hot climates.

Trunk height and soil management choices also impact the microclimate around the bunch. De Rességuier *et al.* (2023) showed that increasing the trunk height raised minimum temperatures around the bunches (thereby limiting frost risk) and lowered maximum temperatures. This effect was greater when grass cover was present (figure I-6-7). However, in absolute terms, minimum temperatures were lower in vineyards with grass cover and maximum temperatures were higher. Vines without grass cover and with high trunks therefore have a more favourable temperature regime in the area around the bunches, with less risk of frost, scalding and the appearance of cooked fruit aromas.

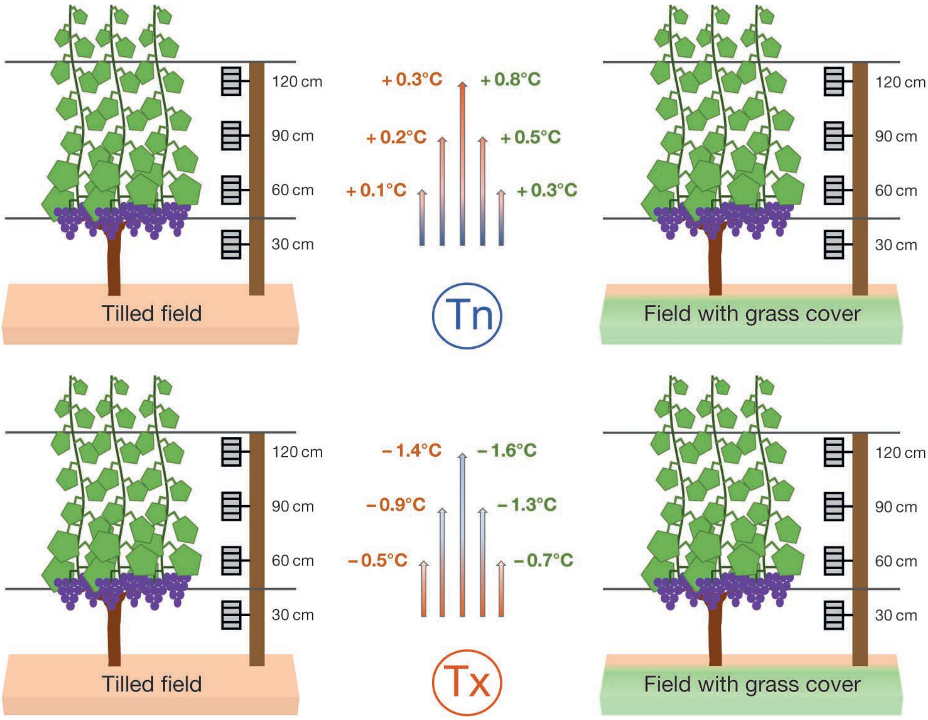

Figure I-6-7. Average differences in minimum (Tn) and maximum (Tx) temperatures between different heights and the effect of soil management on days with extreme temperatures (Tn < −2.5°C and Tx > 35°C). Based on de Rességuier *et al.* (2023).

Adapting annual practices and addressing climate change

The date of the last spring frost is moving forward due to climate change. However, this shift does not necessarily translate to a lower risk of frost, as vines are also budding earlier, which increases how long they are exposed to frost risk. Sgubin *et al.* (2018) showed that the risk will increase in eastern France, decrease in the south and remain stable in the west for most climate simulations. However, such projections come with a high degree of uncertainty (Bois *et al.*, 2023). One way of limiting frost risk is to delay budburst by pruning later. Pruning at the green tip stage (Baggiolini's C stage) can delay budburst of buds left after pruning by around 10 days. Later pruning dates further delay budburst, which can potentially lower sugar content at maturity, but with severe consequences on yield (Zheng *et al.*, 2017; Previtali *et al.*, 2022). The feasibility of late pruning at the vineyard scale needs to be determined, and perhaps implemented only in areas most at risk of frost.

The main impact of climate change on grape composition is the increase in sugar content at maturity, which is already happening in most vineyards (see chapter I-3). Experiments testing various practices have attempted to slow down sugar accumulation in grapes. Recently, Previtali *et al.* (2022) published a meta-analysis of 43 different studies. They showed that the use of antitranspirants could reduce sugar content at maturity by around 1°Bx, and even more effectively when two successive applications were made before veraison. As mentioned above, late pruning can be effective, but it is especially so for vines with low yields. Finally, reducing the ratio of leaf area to harvest weight via hedging or apical leaf removal after veraison reduces the sugar content of grapes in high-yielding vineyards, especially in late-ripening red varieties. Regardless, numerous factors such as the grape variety and the year's climate conditions will impact how effective these practices are. These various factors can also have non-negligible consequences on other components of grape quality, such as phenolic compounds (Van Leeuwen *et al.*, 2019a).

The main grapevine training systems

The main grapevine training systems used in France are single canopy espalier at various planting densities and goblet training. Studies on divided canopy vines, such as the lyre, have yielded promising results, even if their development has remained very limited in France.

Single canopy espalier

In France, espalier (single canopy) is the most widespread training system. In this system, the vines are planted in rows and the vegetation is trellised using stakes and wires (figure I-6-8A). Vines on the row are generally spaced around one metre apart. Inter-row spacing is highly variable (from one to four metres) and determines water consumption, the micro-climate of the vegetation and bunches, yield and production costs (Van Leeuwen *et al.*, 2019b). The system is easy to mechanize and can be adapted by varying the distance between rows, trunk height and canopy height.

Goblet training

Goblet training with vines planted at a moderately low density (2,500 to 4,500 vines/ha) reflects the archetypal Mediterranean vineyard (figure I-6-8B). This training system is very well suited to dry, hot climates. Vines can be grown without irrigation in climates with rainfall exceeding 350 mm/year to produce a high-quality harvest. This system of vine training is widespread in Châteauneuf-du-Pape, which produced an excellent vintage in 2019, despite having only 221 mm of rain between 1 January and 30 September and a summer with very intense heat waves (Van Leeuwen *et al.*, 2022b). The drawbacks of this training system are that productivity is relatively low and harvesting must be done by hand (Deloire *et al.*, 2022). Aside from harvesting, which cannot be mechanized, the production costs for this system are very low, as there is no trellising to set up and maintain, no tying or tensioning to do, and the soil can be easily managed using crossed superficial tillage (Roby *et al.*, 2008). Goblet training is undoubtedly the system that is best suited to a climate that is getting warmer and drier. It is a shame to see so many goblet vines being dug up solely because harvesting cannot be mechanized. The development of a harvesting machine for this system should be a priority for the technical institutes working on adapting grapevine to climate change.

Divided canopy systems

Divided canopy systems allow wide row spacing, which facilitates mechanization and sun exposure for optimal yield in terms of both quality and quantity (Smart and Robinson, 1991; Reynolds and Van den Heuvel, 2009). These systems help the grapes to ripen well,

Figure I-6-8. Different ways of trellising vines. A: single canopy espalier; B: goblet; C: lyre; D: vertical divided canopy (Scott Henry). © Jean-Pascal Tandonnet, INRAE (A, C); Laure de Rességuier, Bordeaux Sciences Agro (B); Thierry Dufourcq, IFV Sud-Ouest (D).

even with fairly high yields, but have the disadvantage of using a lot of water. The canopy can be divided either horizontally (lyre shape, figure I-6-8C) or vertically (with one part of the vegetation growing upward and the other part growing downward, as is the case for the Scott Henry and Smart-Dyson systems; figure I-6-8D). The lyre system has never caught on in France because of the difficulty of mechanizing harvesting. Trials are under way in the Côtes de Gascogne with the Scott Henry system. Studies on these divided canopy systems show good performance in terms of yield and product quality. When setting up training systems, the key factor to be optimized is sun exposure (rather than the number of vines per hectare), unless water availability is a limiting factor.

Conclusion

Whether used to mitigate the effects of climate change or adapt to it, grapevine training systems and soil management practices as a whole are evolving in the context of climate change, offering promising solutions to make winegrowing more environmentally, socially and economically sustainable (Poni, 2023). Training systems and soil management practices must take into account the soil and climate constraints, production targets and resources of each vineyard and the specific characteristics of each vintage. Certain winegrowing practices can be real levers for adapting to climate change (such as agroforestry and the use of plant cover, box I-6-2) and can be combined to make vineyards less vulnerable, especially in terms of water stress (Romero *et al.*, 2022). These solutions must be implemented in a way that suits the scale of the winegrowing operation and the services expected by the producer, particularly in terms of production.

Box I-6-2. How can organic winegrowing practices mitigate the effects of climate change?

The main aim of organic farming practices is to reduce the environmental impact of crops by limiting the use of polluting inputs such as pesticides and synthetic fertilizers. These practices limit soil degradation and promote biodiversity and biotic interactions that support crop health (figure I-6-9). However, there is very little data available to assess their potential in the context of climate change.

Because organic practices use fewer inputs, they help limit CO_2 emissions related to producing those inputs; however, reliance on more mechanized operations requiring fossil fuels outweighs this benefit. Ultimately, the balance can depend on several factors, including the number of times farm equipment is driven over the ground and the power of the equipment used (Tissot *et al.*, 2021). A recent study in Italy on 25 winegrowing estates did not reveal any significant differences between conventional and organic practices for all grape production operations (Ghiglieno *et al.*, 2023). Other authors reported a possible reduction in N_2O emissions in organic winegrowing (Döring *et al.*, 2020). Sustainable soil management practices should aim to minimize erosion and compaction, increase carbon and organic matter content as a source of nutrients and promote biotic processes. These practices all have a positive effect on soil water availability and the soil volume explored by roots (Romero *et al.*, 2022). However, modelling showed that while plant cover could contribute to future carbon neutrality in vineyards, additional measures would be needed for them to become

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genuine carbon sinks (Schultz, 2022). It is important to account for the increase in soil temperature (in addition to air temperature) and changes in water status, which reduce long-term storage capacity. The beneficial effects of higher atmospheric CO_2 levels on yields could offset the negative effects of organic winegrowing practices on productivity (Döring *et al.*, 2020).

Varieties that are resistant to downy and powdery mildew, which can reduce the need for fungicides by up to 80%, will also need to ripen later and be drought and heat resistant to survive climate change. Rootstocks can also be used to combine environmentally-friendly practices with adaptation to future climatic conditions (Ollat *et al.*, 2022).

Figure I-6-9. Sown plant cover in a vineyard in Bordeaux. © Nathalie Ollat, INRAE.

Chapter 7

WATER MANAGEMENT

Thierry Simonneau, Cornelis van Leeuwen, Guillaume Coulouma,
Nicolas Saurin, Isabelle La Jeunesse and Nathalie Ollat

Introduction

As temperatures rise, evapotranspiration will increase until it outstrips soil water recharge by rainfall, particularly in the summer. The result will be water deficits of variable length and ever greater frequency and intensity, during which soil water availability will drop. These circumstances will require winegrowers to explore alternative management choices and practices. With a view to boosting sustainability and water efficiency, the LACCAVE project conducted a range of research to examine diverse viticultural approaches.

The issue of water availability is not a new one for winegrowers. Certain winegrowers have long been using moderate water stress to improve wine quality, especially that of red wines. For example, vineyards have been established on shallow or stony soils, which have a low water storage capacity. As a result, a moderate water deficit develops at the end of the growth cycle. On a less positive note, vineyards have been experiencing exceptionally hot and dry growing years as a result of dramatic inter-annual climate variation. It is therefore interesting to delve into winegrowers' adaptations for buffering the impacts of the hottest, driest years and to witness the new solutions that are emerging.

A bibliography is available for those who wish to learn more about the positive and negative effects of water stress (chapter I-3). This body of information serves as the foundation for creating ideal water management regimes, that is to say how winegrowers work with soil water availability over the course of the growth cycle to attain production objectives.

To follow this trajectory as closely as possible within a specific pedoclimatic context subject to unpredictability, winegrowers can adjust long-term plot production goals or adopt more water-efficient management systems. Additionally, they can increase water availability via specific soil management techniques. Finally, in situations where irrigation is possible, winegrowers should opt for reliable, water-efficient methods that fit with production objectives. Thus, action can be taken both at planting and after grapevine establishment and can engender results that are more or less immediate, reversible or long lasting. This chapter delves into the complex issue of water management and discusses the various approaches that can be used. It also describes the water management challenges that arise within complex landscapes occupied by multiple stakeholders and characterized by a heterogeneous regulatory context, a backdrop against which decision-making around competing forms of water usage must be systemic and long sighted.

Modifying the plant material

Grapevines themselves are a powerful tool for adapting to climate change (see chapter I-5), particularly when it comes to water stress. Choosing the right plant for the job is a long-term solution whose environmental impact can be neutral or positive. At the very least, this choice can help limit the water footprint of the winegrowing operation. Different rootstock-scion combinations lead to differences in a grapevine's ability to access water within the environment and to regulate the degree of transpiration. Consequently, the choice of combination is a serious decision. That said, it is challenging to identify a single trait, whether on the rootstock or the scion, that is capable of predicting a genotype's drought response, setting aside the difficulties associated with field observations. Gambetta *et al.* (2020) has proposed a possible combined proxy: stress distance. This metric is based on four physiological traits, namely maximal transpiration rate, stomatal regulation, turgour loss point and root volume. It is possible to exploit genetic variation in these traits to adapt their values, by utilizing different rootstocks, scions or a variety's clonal diversity.

Varieties can be paired with specific rootstocks to boost their drought tolerance (Ollat *et al.*, 2016a). The most drought-tolerant hybrids are thought to be Rupestris × Berlandieri grapevines (110R, 140Ru, 1103P), whose use is already common in southern France, where droughts are more frequent than in other winegrowing regions. However, rootstocks conferring even greater drought tolerance are available outside of France, and most new rootstock breeding programmes are seeking to improve this trait. A unique experimental vineyard established in Bordeaux is growing grapevines formed from combining 5 varieties with 55 rootstocks (including 25 that are as yet unregistered in France; see box I-5-2); the goal is to produce new standards of reference and identify rootstocks adapted for use under more extreme conditions (Marguerit *et al.*, 2019). How well grapevines cope with water scarcity is determined by key root traits such as root depth, branching density, diameter, developmental plasticity in response to water availability and water extraction capacity (Marguerit *et al.*, 2012; Ollat, 2014). However, there are strong interactions between soil type and planting practices. Once commonly used in Mediterranean vineyards, on-site grafting (i.e. grafting after the rootstock has been planted) is a technique that can encourage robust root development. Certain rootstocks that increase grapevine vigour also enhance drought tolerance (140Ru, 110R), although this relationship is not systematic. The choice of rootstock can also influence transpiration regulation and water use efficiency, i.e. the biomass produced per unit of water consumed (Marguerit *et al.*, 2012).

Grape varieties differ greatly in their responses to water stress. It is important to account for trade-offs between grape yield and composition (Serrano *et al.*, 2022). When switching to a more drought-tolerant variety, winegrowers must consider the potential production value (Van Leeuwen *et al.*, 2020) as well as local water availability dynamics (e.g. occurrence of permanent versus periodic water stress, presence or absence of co-occurring thermal stress). This choice has long-term consequences, although regrafting on site can be used as a corrective mechanism. While there is unfortunately no global system for classifying variety drought tolerance, certain Mediterranean varieties are considered to fall on the tolerant end of the spectrum (table I-7-1). Grape varieties differ dramatically in physiological traits related to drought tolerance, such as water use efficiency (easily estimated via carbon isotope ratios; Bota *et al.*, 2016), leaf and stem stomatal characteristics (Faralli *et al.*, 2022) and hydraulic characteristics (Lamarque *et al.*, 2023), stomatal regulation (Dayer *et al.*, 2020 and 2022; Plantevin *et al.*, 2022) and defoliation sensitivity (Van Leeuwen, personal communication). At the same time, Serrano *et al.* (2022) found that grape varieties that maintained high yields and optimal grape composition under water stress did not have the highest levels of water use efficiency (estimated via must carbon isotope ratios).

Table I-7-1. Examples of grape varieties generally considered to be rather drought tolerant or rather drought intolerant. Based on (1) Champagnol, 1984, (2) Dayer *et al.*, 2022, (3) Plantevin *et al.*, 2022, (4) Serrano *et al.*, 2022, (5) Van Leeuwen (personal communication, VitAdapt observations from 2022, see box I-5-1) and (6) Lamarque *et al.* (2023).

Rather tolerant	Rather intolerant
Cabernet Sauvignon (3, 5, 6)	Merlot (3)
Grenache (1, 2, 3, 4, 5)	Tempranillo (3, 4, 5)
Roussane (3, 5)	Syrah (3, 5)
Xynomavro (3)	Viognier (3)
Mourvèdre (3, 4)	Sémillon (2, 3, 5)
Bobal (4)	Forcallat (4)
Garnacha Peluda (4)	Garnacha Tintorera (4)
Marzuela (4)	
Moribel (4)	
Xynisteri (3, 5)	
Cinsault (1)	
Carignan (1, 5)	

Recent studies of Grenache and Tempranillo clones (Mairata *et al.*, 2022; Tortosa *et al.*, 2022) have found that significant variation exists in water use efficiency among clones of the same grape variety. Finally, research in Australia has looked at unirrigated Cabernet Sauvignon grapevines growing in long-established plots with varying levels of soil water storage (Pagay *et al.*, 2022); the results indicate that grapevines experiencing low water availability (i.e. growing in shallow soils) can acquire a certain degree of drought tolerance. In a greenhouse experiment, clonal progeny of these grapevines displayed the same tolerance as their parents, which expressed itself as improved gas exchange, better photosynthetic performance and greater water use efficiency in response to water stress (Nagahatenna *et al.*, 2022). These results are quite promising, as they illustrate that grapevines can acclimate to water stress and that they may inherited favourable behaviours thanks to intergenerational stress priming.

Soil preparation and management

The practices used for vineyard establishment and soil management have a major influence on soil water transfer and storage. At present, viticultural operations tend to be mechanized, chemical weed control is common, and soil organic matter is less frequently managed. This state of affairs has led to often unfavourable changes in soil characteristics, including declines in water storage capacity. First, the structure of the soil surface determines the soil's capacity to absorb rainfall, thereby affecting run-off (figure I-7-1). Soil infiltrability determines the partitioning of rainfall into infiltration and run-off. In the context of climate change, higher infiltrability is particularly desirable, given that the increase in intense rainfall events will lead to increased run-off. If infiltrability is poor, grape production will be more dramatically affected by global warming, as evapotranspiration increases and cumulative rainfall decreases. Thus, soil preparation at planting and post-establishment management practices provide an opportunity to better adapt vineyards to climate change conditions.

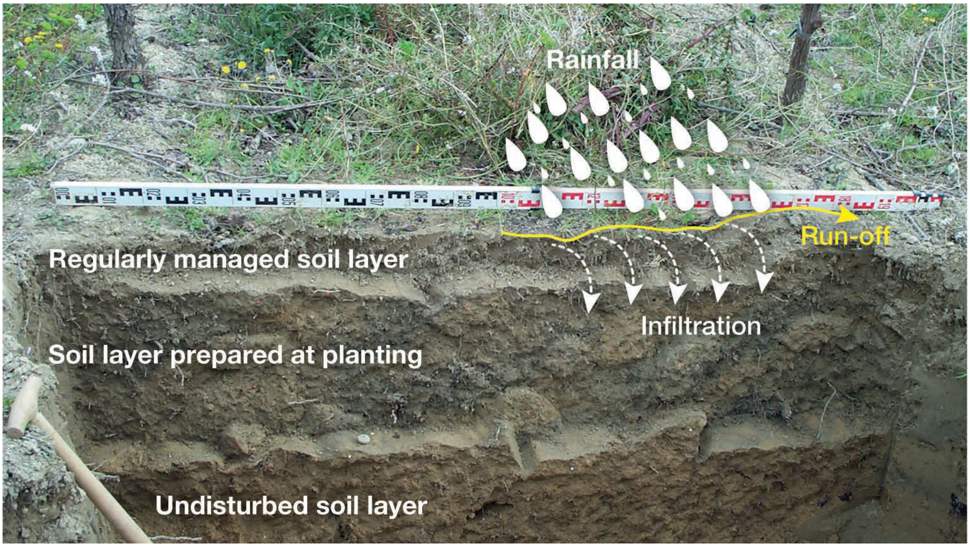

Figure I-7-1. Vineyard soil profile showing the main factors affecting water transfer and storage. © Guillaume Coulouma, INRAE.

Shaping soil water capacity at planting

The available water capacity of vineyard soils mainly depends on how deep grapevine roots can extend. This depth is generally equivalent to the soil depth but may also be affected by obstacles (e.g. presence of a ploughpan) or inhospitable soil layers (e.g. containing low oxygen levels during certain periods of the year). The available water capacity also depends on the soil's water retention capacity. The latter is defined by constant inherent characteristics such as texture as well as by more variable characteristics (e.g. structural state, organic matter content) that can be modified by viticultural operations. In particular, when preparing the soil for grapevine establishment, several practices can significantly affect available water capacity. Deep ploughing (working depth of 70 cm) and ripping (working depth of 1 m) can enhance vine rooting depth in moderately deep soils (common in vineyards), thereby increasing available water capacity (figure I-7-2). However, deep ploughing also tends to cause structural degradation, resulting in reduced available water capacity and disruptions to the rooting of young grapevines; soil functions may even deteriorate. In shallow soils, this form of ploughing also dilutes soil organic matter by mixing it with minerals from the bedrock, which also results in reduced available water capacity (Coulouma *et al.*, 2006).

Figure I-7-2. Deep ploughing operations prepare the soil for a new vineyard. © Guillaume Coulouma, INRAE.

Limiting run-off and promoting infiltration post establishment

Soil management practices can be used to improve available water capacity in established vineyards. Experimental field research in small plots, large plots and watersheds has shown that the presence of vegetative cover promotes greater, more consistent infiltrability and reduces run-off by allowing moderate rainfall (less than 20 mm per hour) to successfully enter the soil (Molénat *et al.*, 2021; Alletto *et al.*, 2022). Tilling the soil before a rainfall event can also augment infiltrability. However, when this technique is used, infiltrability rapidly diminishes over the course of the current and subsequent rainfall events due to the gradual formation of a structural crust potentially several centimetres thick (Pare *et al.*, 2011). Organic matter content greatly affects crust size and infiltration in the tilled soil surface (average depth of 0 to 15 cm) (figure I-7-3). Combining more organic fertilization with natural or sown grass cover can significantly increase available water

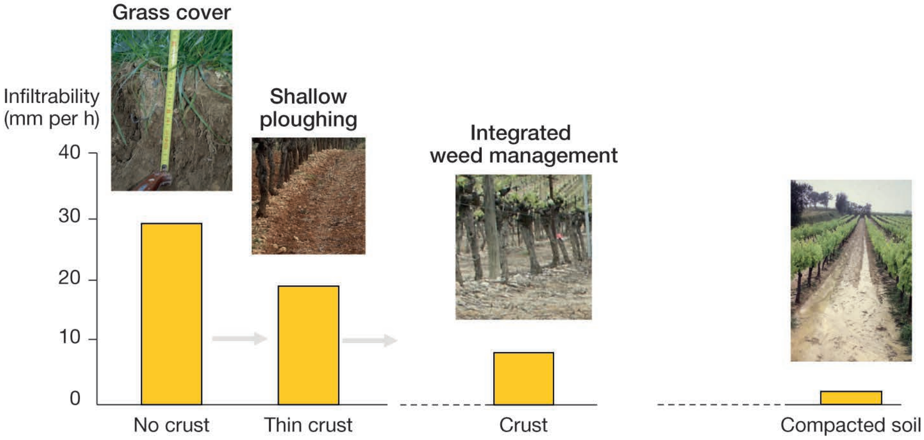

Figure I-7-3. Effects of conventional soil management practices on surface-level infiltrability.

capacity and limit run-off, a factor responsible for progressively eroding vineyard soils. However, management strategies must prevent competition for water between the grass cover and grapevines during the summer.

Vineyard layout and training systems

Grapevine training systems focus on vineyard spatial layout (spacing within and between rows), grapevine architecture (trunks and branches), and canopy management. The choice of management system strongly influences vineyard water consumption because it affects the water available to each plant, depending on the proportion of solar radiation intercepted by the plants and the relative amount of leaf area exposed to radiation. Thus, management systems are powerful tools for adapting vineyards to the local availability of water resources.

The soil surface area associated with a given grapevine is determined by planting density. When planting density equals 10,000 plants per hectare, each plant has access to 1 m^2 of surface area; for a planting density of 2,500 plants per hectare, this figure is 4 m^2. At lower planting densities, assuming that root depth remains the same, each plant has access to a greater volume of soil, which translates into greater access to water resources. According to Champagnol (1984), the roots of a grapevine occupy up to 10 m^2 of surface area in more fertile soils and 4 m^2 in less fertile soils. Planting densities of less than 2,500 plants per hectare are rare, which suggests that root growth is not a limiting factor. For all planting densities, preliminary steps must be taken to encourage deep rooting: the soil must be prepared appropriately, the plant roots should be trimmed to 4–5 cm, especially if a mechanized planter is to be used (Protet *et al.*, 2022), and grape production should be limited as much as possible over the first two to three years (Champagnol, 1984).

The grapevine training system also plays a key role in mediating grapevine interception of solar radiation, the energy that fuels evaporation during transpiration. Row spacing can influence the amount of radiation intercepted (Smart, 1973). When rows are closer together (e.g. one metre apart), the grapevines intercept nearly all of the incoming radiation. In other words, little radiation reaches the ground surface. The result is an increase in grapevine transpiration per unit area of soil surface, leading to a concomitant increase in water consumption. When rows are farther apart, grapevines consume less water per unit area of soil surface (Van Leeuwen *et al.*, 2019). This effect has been seen in other crops as well. In dry regions, fruit trees are planted at lower densities (see Guerfel *et al.*, 2010 for an example involving olive trees), and foresters have observed lower levels of water consumption in thinned forests (Gyenge *et al.*, 2011; Giuggiola *et al.*, 2012). Canopy height is also varied to modify radiation interception. Models can predict the effects of row spacing and canopy height on grapevine water consumption (Lebon *et al.*, 2003), information that can then be integrated into the water balance and whose impacts can be assessed. These issues were explored in chapter I-6.

Unique grapevine training systems have emerged in the Mediterranean basin, where winegrowers have always faced low water availability (Santesteban, 2020). The best-known strategy is the use of goblet architecture, a system in decline but that continues to be employed across relatively large surface areas (Deloire *et al.*, 2022). Surprisingly, research has yet to explore why goblet architecture results in extremely high levels of drought tolerance. In many areas, this system can produce high-quality wine, despite annual rainfall levels of less than 400 mm and the absence of irrigation. The explanation likely lies in the fact that the system results in lower levels of solar radiation interception per unit area of soil surface, given that goblet architecture almost always goes hand in hand with planting densities that are relatively low for the Mediterranean basin (2,500 to 3,000 plants per hectare). Root vigour could also be another explanation. One negative consequence of these low planting densities is moderate yields. Anecdotally, vineyards on the volcanic island of Santorini use another distinctive system: basket-like architecture that is also highly adapted to extremely dry conditions (Xyrafis *et al.*, 2021). We should be taking a much closer look at these systems, given that water resources are dwindling and accessing irrigation water is difficult. It is ironic that, as droughts are becoming an increasingly large challenge for vineyards, it is these drought-tolerant systems that are most often uprooted, although they may admittedly be less productive.

Irrigation: ideal versus real

Irrigation has long been a common practice in the vineyards of the western hemisphere. It has only more recently been adopted in the (French) Mediterranean, and it is one of the major strategies used by winegrowers to adapt to climate change.

Worldwide, vineyards have traditionally used gravity-fed or flood irrigation systems. Since the early 1990s, there has been an increase in more water-efficient, targeted irrigation systems, such as drip irrigation. More recently, underground irrigation systems have come onto the scene. These systems are even more efficient because there is no direct evaporation of the irrigation water. They can also reduce the need for weed management. On the downside, they are more costly and require more maintenance.

Ideally, irrigation practices should utilize accurate estimates of grapevine water status and incorporate an understanding of phenology-specific responses to water stress.

Several techniques can be used to characterize grapevine water status (Rienth and Scholasch, 2019). The reference method is to use a pressure chamber to measure leaf water potential. Other indicators of grapevine water status can be measured directly or indirectly. Direct methods include quantifying the degree of stomatal conductance using portable porometers, estimating transpiration using sap flow sensors, determining leaf temperature using infrared thermometers, and assessing apical growth visually. An indirect method could be characterizing water availability in the root zone using tensiometers. It is also possible to model soil water balance using estimates of the soil water holding capacity and evapotranspiration values calculated from a meteorological database. These estimates can be refined by measuring plant characteristics (predawn water potential, measured at the end of the night) or soil characteristics. Method choice will depend on the trade-off among different constraints such as cost, ease of use, information utility, the degree of temporal resolution and the degree of spatial resolution.

Irrigation regimes have been defined for specific production objectives (e.g. grape juice, white wine, red wine, still wine), drawing on scientific and empirical information about optimal grapevine water status at each phenological stage and for a given level of water stress (Ojeda, 2007; Ojeda and Saurin, 2014). The general recommendations are as follows:

- at the beginning of the growth cycle, providing a reasonably good water supply will favour shoot growth;
- satisfactory water status around the time of flowering will ensure that the fruit set rate in the current year and early flower development in the following year are unaltered;
- water stress that occurs before veraison, during berry herbaceous growth, will limit potential berry volume without affecting cell division. A modulated reduction in berry volume may even be the goal, as it can increase the quality of red wines intended for still beverages;
- post-veraison water status largely determines wine type. As water stress increases, so do the concentrations of quality-related components (e.g. phenols, aroma precursors, sugars), compensating for the lower yields that largely result from reduced berry size. That said, it is important to avoid excessive water stress to preserve the aromas of white wines and to ensure reasonable levels of tannins, acidity, astringency and alcohol in red wines;
- after harvest and before leaf fall, grapevines need to recover their water status to promote photosynthesis and build up reserves for the next growth cycle.

Winegrower's irrigation strategy should align with the ideal water management regime for their production objective. To moderately limit soil water availability, the amount of irrigation will often represent a fraction of expected evapotranspiration. This approach is known as deficit irrigation (Chaves *et al.*, 2010). An advantage of deficit irrigation is that it restricts the water lost via transpiration; above a certain level, additional water only provides extra stability in water status without yielding further photosynthetic gains (Simonneau, 2023). An alternative to deficit irrigation that yields at least equivalent results is partial root zone drying, in which each side of a row is irrigated during alternating time steps (Dos Santos *et al.*, 2003), allowing for different weed or grass management strategies in the inter-row.

In France, vineyard irrigation regimes must respect regulatory standards, particularly when grapes are destined to produce protected designation of origin (PDO) wines. This framework was established by French Decrees no. 2006-1526 and 1527 of 4 December 2006, which were amended by French Decree no. 2017-1327 of 8 September 2017. The latter specifically focuses on grapevines used in PDO wine production. All three regulatory texts are part of the French Rural and Maritime Fisheries Code (CRPM). Up until 2023, all irrigation was banned between 15 August (veraison) and the harvest. The recent French Decree no. 2023-735 of 8 August 2023, changed this start date from 15 August to 15 September.[27]

Certain public policies are aimed at encouraging winegrowers to adopt specific irrigation systems. For example, specific funding has been available since 2008 through the Common Market Organization (CMO) regime for the viticulture and wine industry. This instrument provides financial support to winegrowers who are restructuring their vineyards, which includes installing drip irrigation. FranceAgriMer allocates this aid on a

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[27] https://www.legifrance.gouv.fr/download/pdf?id=GRqEXBtcolqqdSAistw5ZMkXQ6zD77WWCC2B1aFBUYU

flat-rate basis (up to €800 per hectare). Winegrowers must first provide proof of individual water rights or of membership in a water users' network. Furthermore, on-site inspections are regularly performed.

According to FranceAgriMer, between 2008 and 2018, this aid programme resulted in the installation of drip irrigation systems on more than 23,700 hectares of grapevines in the Languedoc-Roussillon winegrowing region. According to the Association for Irrigation Users in the French Mediterranean (AIRMF), in 2017, over 32,000 hectares of grapevines in the Languedoc-Roussillon winegrowing region were under irrigation, representing 14% of the surface area covered by vineyards. Furthermore, vineyards accounted for 40% of the total surface area under irrigation. Based on this metric, grapes are the most irrigated crop in the region. However, the water volumes withdrawn remain moderate compared to those for other crops. Given that, within an ideal water management regime, water

Box I-7-1. Could vineyards use treated wastewater for irrigation?

Climate change and increasing demands for irrigation water mean there is a need to consider new solutions, such as the reuse of treated wastewater. This idea is receiving growing support from international organizations, including the European Union and the Food and Agriculture Organization of the United Nations. In France, the reuse of treated wastewater was a recommendation that came out of the National Symposium for Water (2019) and the National Debate on Water (2022).

In 2010, around 10% of the world's irrigated land, or 20 million hectares, was irrigated with untreated or diluted wastewater. Only 500,000 hectares were irrigated with treated wastewater. In arid and semi-arid regions, levels of wastewater reuse may be as high as 90% (Israel, Jordan). They are 25%–30% in the southern Mediterranean, 14% in Spain and 8% in Italy. In France, less than 1% of treated wastewater is reused. The longest-running and best-known experimental sites for wastewater irrigation are located near Noirmoutier (300 hectares of potatoes) and Clermont-Ferrand (700 hectares of wheat, beet and corn under irrigation since 1999).

Over 10 years ago, near Narbonne, the local government launched the first initiative to irrigate vineyards with wastewater. These efforts led to advances in the realm of technical and economic feasibility. A pilot project near the seaside resort of Gruissan is irrigating 80 hectares of grapevines with treated wastewater but is grappling with salinity-related issues. Another pilot project in Roquefort-des-Corbières, a small village of 1,000 inhabitants, is irrigating 15 to 20 hectares of a 600-hectare vineyard.

These projects have laid the groundwork for the regional deployment of this irrigation strategy. However, scaling up remains a complex undertaking. Current health and environmental regulatory standards are daunting, but European regulations are taking a turn that should facilitate the launch of wastewater irrigation projects. These projects involve a wide range of stakeholders: local sanitation authorities, the company running the wastewater treatment plant and tertiary treatment procedures, the regional union for agricultural water users (ASA), and everyday citizens. All stakeholder needs and expectations must be clearly defined and communicated from the outset. Given the strategy's high investment costs (additional levels of treatment, supply networks), it would be ideal to identify additional uses for the treated wastewater (urban cleaning and sanitation, irrigation of green spaces, firefighting and groundwater recharge). In conclusion, the reuse of treated wastewater is one solution among many. It could be combined with other vineyard management strategies, such as the appropriate choice of grape varieties or planting densities.

inputs should only partially compensate for water losses, it is recommended that annual usage volumes remain between 500 and 1,000 m^3 per hectare (50–100 mm), depending on the year's rainfall.

Other solutions will need to be found, though, because demand for new or expanded water distribution networks is soaring. Continuing network modernization efforts can bring about major water savings. Alternative approaches are being developed, such as the reuse of treated wastewater (test site: ~100 hectares near Narbonne; see box I-7-1). For areas without network access, it is worthwhile to explore solutions involving water transfer or individual or collective water storage. While winegrowers can employ a variety of proven irrigation solutions, higher-level water management decisions must be made collectively and involve all regional stakeholders.

Winegrowing and water resource management policies

Many professionals now believe watering grapevines is key to confronting droughts and spring frosts, making it a major climate change adaptation strategy in France (Bertrand *et al.*, 2020; Santillán *et al.*, 2019), and demand for irrigation water is climbing fast. This situation gives rise to questions about the relationship between viticultural water usage and the broader spatial and temporal management of water resources.

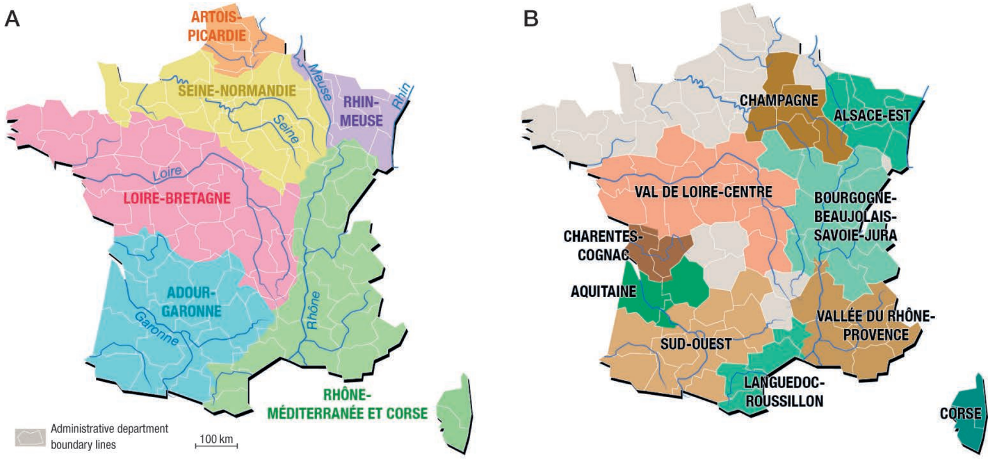


Figure I-7-4. Delineation of France's metropolitan water districts (A) and winegrowing regions (B). Source: French Ministry of Economy and Finance. © Dominique Andrieu, Maison des Sciences de l'Homme Val de Loire (2023).

First, irrigating grapevines to adapt to climate change will place greater pressure on water resources, whether demands are coming from winegrowing regions that already use irrigation or those that have newly adopted the practice. In France, everyone technically has the right to use water resources. However, water must be shared among agricultural and non-agricultural users, and access is heterogeneous within and across winegrowing areas. In other words, vineyard irrigation cannot occur in a vacuum because decision-making around water resource management must consider the needs of multiple usage categories. In Europe, water resource management occurs at the scale of the river basin, in accordance with the Water Framework Directive (2000/60/EC[1]). France has seven metropolitan water districts, each with its own master plan for water use development and management (SDAGE) that is updated every six years. These district-specific plans are built based on the spatial boundaries of the country's major watersheds (figure I-7-4A), which differ from the spatial boundaries of the country's winegrowing regions (figure I-7-4B) and their PDO areas.

Within each water district, regional governments request authorization for their water use development and management plans (SAGEs), which define the region's water and river management strategies; SAGEs emerge from a voluntary consultation process involving local stakeholders. All categories of water usage have representatives on a local water commission, who serve alongside elected officials. At present, SAGEs are applied to 54% of France (Gest'eau, 2023), and, on average, SAGE development takes nine years (Gest'eau, 2023). Thus, recognition of a new usage type, whether at the district level (SDAGE) or a more local level, typically requires the patient navigation of a long process of consultation and dialogue. For this reason, winegrowers will be more successful in having their voices heard in water management settings if viticulture has a stronger influence on regional planning directly related to water resources. Yet, this reality is often overlooked when irrigation is described as an "easy" adaptation strategy to implement. Indeed, this landscape is marked by fierce competition for water resources (La Jeunesse and Quevauviller, 2016), whose intensity has been amplified by France's recent severe droughts. Conflict occurs among usage categories (e.g. consumption for energy production or nuclear power plant cooling, agricultural irrigation, household needs, ecological continuity of waterways, outdoor recreation) as well as within usage categories. Another source of conflict is that access to water is heterogeneous in winegrowing regions, for either technical reasons or inequities in infrastructure funding, which are among the new causes of vineyard relocation (Thermes *et al.*, 2020).

An additional layer is the temporal dynamics of water supply: the timing of water use in vineyards differs depending on its purpose. When grapevines are sprayed with water to provide protection against spring frosts, water usage generally occurs in April, the end of the groundwater recharge period. Drip irrigation uses water at other times of year. Moreover, these two uses employ different amounts of water, whose magnitudes are also affected by grapevine spatial location. However, both uses must be given full consideration during water management decisions.

It is important to recall that, until 2023, irrigation was banned between 15 August and the harvest (article D665-17-5 of the CRPM) for all wine grapes. As of 9 August, 2023, irrigation is allowed until 15 September and after the harvest for grapes intended for protected geographical indication (PGI) wines and wines without geographical indication (WWGI). PDO winemakers can request an exemption allowing irrigation between 1 May and 15 September, which may or may not be granted by the French National Institute for Origin and Quality (INAO) depending on vintage characteristics and the preliminary approval of the relevant Defence and Management Organization (ODG). If the exemption is granted, the irrigation period is the same as for PGI wines and WWGIs. However, INAO does not have an ad hoc commission capable of studying the hydrometeorological conditions in the specific PDO areas from which exemption requests arrive and cannot facilitate regional access to irrigation water. Thus, issues around access must be dealt with locally, in the regions where wine production is occurring.

Conclusion

To cope with climate change, the viticulture and wine industry will need to transform its relationship with water management. Solutions must be defined on a case-by-case basis, accounting for climatic uncertainty, the many factors limiting water availability, and the relationships among different facets of the industry.

First, it is important to recall that short-term meteorological predictions, especially of rainfall, are associated with a high degree of uncertainty at the local level (i.e. the plot). Winegrowers must thus grapple with any misalignment between the shifting water supply (provided by precipitation and potentially irrigation) and fluctuations in grapevine needs, defined by the production objective (and the relevant technical strategies) and by the atmospheric factors affecting evapotranspiration. During this balancing act, the goal is to

Box I-7-2. Agrivoltaics and climate change

Agrivoltaics combines the production of crops and photovoltaic energy. This dual use of a single land surface is similar in principle to agroforestry (Dupraz and Liagre, 2008). Decarbonized energy production is one of the policy directions being pursued to deal with climate change.

The major disadvantage of photovoltaic systems is that they need to be installed across vast surface areas because of the technology's current inefficiency, which is unlikely to change in the near future. In this context, agricultural land surface may represent an untapped resource. Farmers view agrivoltaics as a potential source of additional income, given that these systems are marketed as prioritizing agricultural production.

However, research on crops grown under solar arrays has observed significant negative effects on variables such as growth, development, photosynthesis, water fluxes, yield and microclimatic conditions (Marrou *et al.*, 2013a; Juillion *et al.*, 2022). These impacts seem to be caused by the lower levels of incident solar radiation reaching the plants. Sometimes researchers have seen an increase in radiation use efficiency (Marrou *et al.*, 2013b), which indicates that agrivoltaic systems could be optimized to boost overall productivity per unit area of agricultural land (Dupraz *et al.*, 2011; Édouard *et al.*, 2023).

In vineyards, photovoltaic arrays could serve as a climate change adaptation strategy because they provide shade. The main hypothesis is that an as-yet-undefined amount of shade can help temper summer microclimatic conditions, especially the excessively high temperatures experienced by grapes, and can limit organic acid degradation and sugar production. The goal would be to improve the technological, polyphenolic and aromatic quality of grapes and wines, ideally without affecting yields (or by keeping reductions within economically acceptable margins). Photovoltaic arrays might also furnish a measure of protection against spring frosts.

Shading regimes could be fine-tuned to the specific needs or constraints associated with grapevine phenology. Future research should delve deeper into system optimization and examine scenarios in which milder microclimatic conditions are an acceptable trade-off for lower incident solar radiation and photosynthesis levels. It may be that declines in photosynthesis will be offset in the long term by increased levels of atmospheric CO_2, The production of high-quality wines may even stand to benefit from efforts to redefine source-sink equilibria and implement phenology-specific reductions in incident solar radiation.

adhere as closely as possible to the ideal water management regime mentioned earlier. As the growing season progresses, deviations become less likely, and strategic practices (inter-row cover destruction, leaf thinning, irrigation) can be implemented to obtain rapid effects, allowing production objectives to be achieved.

However, as climate change increases the frequency of summer droughts, water management regimes will be more likely to go off course. Winegrowers must therefore redefine their objectives and adopt more radical approaches, starting at planting.

A systems view of water and wine

Climate and precipitation

What is drought?
When does it occur?
At what intensity?

What about excess water?

Risks

- Impacts on soil: erosion, surface state, organic matter, etc.
- Impacts on grapevines: vigour, yield, production quality
- Socioeconomic impacts: production sustainability, stakeholder vulnerability
- Other environmental impacts: biodiversity, landscape, wildfire, etc.

Status of water resources

- Choice of soils with high water storage capacity
- Water supply infrastructure and equipment
- Quality
- Water management
- Accommodations around shared usage

Technical strategies

- Tilling, grass cover and canopy management
- Drip irrigation
- Drought-tolerant varieties and rootstocks
- Canopy management system, planting density

Production objectives

- Yield and quality
- Value creation
- Production requirements
- Costs and benefits

Perceptions and expectations

- Image of the terroir
- Consumers
- Coexistence

Governance, regulations, other categories of water use, collective and individual strategies

Encouraging participatory and forward-looking approaches: co-construction of strategies, French National Observatory for Water Stress, collective resource management

Figure I-7-5. Main factors involved in water management strategies within vineyards. © INRAE.

These approaches should be customized to the pedoclimatic conditions of each plot by espousing tailored rootstock-scion combinations, soil preparation strategies, planting densities, pruning systems and trellising systems. When possible, risks can be minimized via a crop diversification regime and a well-reasoned cropping plan that is adapted to soil water holding capacity. Additionally, various shading systems are under development. They may help save water but could also hurt production when water stress is moderate (see box I-7-2). Making structural modifications to plots (low walls, terracing embankments, row orientation) can help limit run-off and erosion. All these approaches must be adapted to local conditions. Overall, system resilience will be enhanced if (a) production objectives can be modified to fit with future patterns of water availability, with a safety margin defined by the local frequency of extreme climatic events, and (b) technical strategies allow for adaptive water management, both of inputs and withdrawals.

Finally, the impacts of hot dry years need to be assessed at several industry scales, accounting for biophysical and socioeconomic circumstances. Winegrowers do not engage in decision-making within a vacuum. Their choices are often constrained by regulations or socioeconomic trade-offs that are beyond their control (figure I-7-5). These issues are particularly salient in the case of irrigation. The negative environmental impacts of irrigation and the overall costs of water withdrawals and transport must be part of the equation used to assess the sustainability of this viticultural practice. Choices will heavily depend on socioeconomic factors, notably consumer perceptions and the equilibrium between the interests of the general public and those of industry professionals. Additionally, irrigation may be impossible for some plots within vineyards or for entire vineyards. Consequently, it might be necessary to rethink vineyard distribution patterns at the landscape level, given the disparate effects of climate change and differences in water access. To tackle this momentous challenge, we will need to promote participatory approaches that bring together all regional stakeholders.

Chapter 8

OENOLOGICAL SOLUTIONS: ADAPTING THE WINEMAKING PROCESS

Philippe Darriet, Jean-Roch Mouret, Jean-Marie Sablayrolles and Alain Samson

Introduction

Adapting to climate change will require major shifts in viticultural practices, particularly with regards to grape variety choice and training systems. These shifts are largely medium- to long-term measures.

In the short to medium term, changes in oenological practices have a vital complementary role to play. The idea is to deploy winemaking tools and strategies that are better able to deal with the shifts in grape composition induced by climate change. These shifts will extend beyond excessive sugar content and low acidity levels. There will also be changes in the concentrations of essential sensory components such as polyphenols and volatile odorant compounds in wine.

Viticultural and oenological strategies must act synergistically and aim for two context-dependent objectives: to preserve the main characteristics of current-day wines, applying a controlled designation of origin perspective, and to optimally generate products from grapes with a new range of properties. In the case of both goals, action can be taken during grape harvesting as well as during wine production and maturation.

Adapting grape-harvesting methods

Under climate change, grapes will likely be ripening when environmental temperatures are high and grapevines are experiencing significant water stress, which could lead to defoliation. Thus, winemakers will need to anticipate that fermentation will transform these grapes that are rich in sugar into higher-alcohol wines. Another related consequence is that grapes may shrivel and experience a decrease in total acidity with a concomitant increase in pH. These trends can be seen in red wines produced in Occitania, France's southernmost region, over the past 20 years (figure I-8-1). In extreme cases, grapevines may face insurmountable levels of water stress, and grape ripening may come to a halt. As a result, winemakers will need to adjust their harvest dates and harvesting methods.

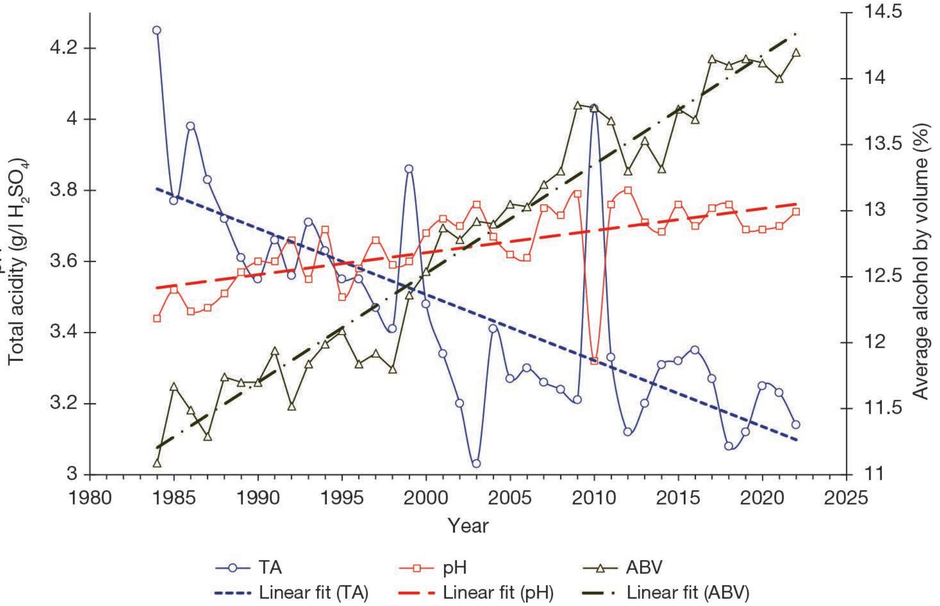


Figure I-8-1. Changes in total acidity (TA), pH and average alcohol by volume (% ABV) from 1984 to 2022 for more than 2,000 red wines produced in Occitania (based on annual samples). Data: Dubernet laboratory (Narbonne, France), figure: INRAE Pech Rouge Experimental Research Unit (Gruissan, France).

Adapting harvest dates

As a general rule, winemakers choose their harvest dates based on vineyard observations, grape ripeness tests and production objectives. This decision is guided by past experience, assessments of grape ripeness (or overripeness) and target wine characteristics. The primary criterion may become environmental conditions, as climate change will cause shifts in meteorological circumstances and grape traits. During ripeness tests, representative grapes can be sampled from target fields, and their basic composition can be analysed (e.g. sugar content, acidity). The decision-making process could be further informed by complementary information from taste tests conducted on individual berries or representative samples of berry groups, along with analyses of phenolic compounds, assimilable nitrogen content, malic acid levels and potential aroma profiles. In this vein, winegrowers could receive training in berry tasting to gain a better sense of potential winemaking trajectories.

Climate change will affect the composition of mature grapes. Thus, the characteristics of ripening grapes can point the way to appropriate adjustments. For example, winegrowers might choose to adopt a two-tier harvesting approach: conducting a first harvest before the grapes are fully ripe to obtain less sweet, more acidic berries and conducting a second harvest when the grapes have completely ripened. In this approach, blending would occur after wine production. Alternatively, winegrowers might decide to selectively remove any shrivelled grape bunches ahead of the main harvest (performed manually or mechanically). A third possibility would be to harvest grapes of different varieties on the same date, after running some preliminary trials and depending on regulatory constraints. In this scenario, grapes with compositional differences (e.g. in acidity, sugar content, aromatic compounds or polyphenolic compounds) could be combined during wine production to form a single cuvée, using grapes or pressed grape juice. These practices would be more straightforward to apply when producing dry white or rosé wines. However, in the case of red wines, the use of unripe grapes can result in higher levels of astringency and bitterness, given that maceration may lead to the extraction of mainly phenolic compounds. Researchers have been exploring whether unripe grapes, collected before the main harvest, could be used to shape the characteristics of Pinot Noir and Tannat wines (Piccardo *et al.*, 2019). These grapes were pressed, and the resulting juice was stored at low temperatures before being added to the regularly harvested ripe grapes, which had been crushed and drained. The above experimental approach helped achieve suitable grape acidity levels and sugar content but should be employed with caution and adapted depending on grape variety. Preliminary experimentation is crucial, especially when making wine from black grape varieties. Grape selection could occur during the harvest or be facilitated by grape-sorting mechanisms, in association with total or partial stem removal and subsequent grape crushing. For example, winegrowers can use commercially available densimetric sorting devices to separate grapes based on sugar content, a procedure during which destemmed berries are placed in a sugar solution.

The effects on a wine's sensory and analytical characteristics will vary greatly, depending on wine type (e.g. dry white, rosé, red, sweet, sparkling) and the nature of any pre-fermentation procedures.

Adjusting harvesting methods

Harvesting methods can also have a pronounced impact on wine characteristics. Between the harvest (whether manual or mechanical), the grapes' arrival at winery facilities and the implementation of any pre-fermentation procedures, there is a period during which various chemical and biochemical phenomena occur, depending on the temperature of the harvest and any treatments applied. These phenomena can influence (1) the non-selective extraction of grape compounds, particularly those found in the skin, (2) the chemical and enzymatic oxidation reactions that occur in the grape juice, leading to browning and (3) the development of the microorganisms involved in fermentation. The effects of these phenomena are more dramatic at higher grape temperatures.

Grapes should consequently be harvested at low temperatures (below 20°C), especially when destined to produce white and rosé wines. Additionally, the harvest should be delivered as rapidly as possible to winery facilities. Following these recommendations helps preserve grape quality and wine aromatic character. Ever since harvesting machines arrived on the scene, it has become common for grapes to be harvested early in the morning, or even at night, when temperatures are cooler (figure I-8-2). In southern France, some winemaking cooperatives require their members to deliver their grapes by a certain time in the morning. However, as global temperatures increase, even these steps may be insufficient on certain days, particularly in August or early September when, on certain days, nocturnal air and grape temperatures may never fall below 25°C. In such situations, grapes must be cooled down upon arrival at winery facilities, which entails energy costs.

This process can utilize dry ice in the form of pellets or sticks or cooling tunnels that employ liquid nitrogen or carbon dioxide. It takes around 1–1.2 kg of dry ice to lower the temperature of 100 kg of grapes by 1°C. The cooling process also helps limit the extraction of grape compounds prior to pre-fermentation procedures, which can be useful when harvesting extremely ripe grapes. Furthermore, it constrains the enzymatic oxidation of grape aromatic and phenolic compounds, a reaction that can affect wine quality. Additionally, steps should be taken to prevent the grapes from getting crushed during harvesting, transport and arrival at the winery facilities; otherwise, there will be excessive non-selective extraction of grape compounds.

This same set of measures (cooling and preserving grape integrity) can help limit the development of unwanted microorganisms on the grapes. In this regard, bioprotection can be a helpful complementary strategy: yeasts in genera other than *Saccharomyces*, such as *Torulaspora delbrueckii* or *Metschnikowia pulcherrima*, can be directly added to the harvested grapes to help restrict the development of undesirable bacteria or oxidative yeasts. For extremely ripe grapes, a dose of 10–20 grams per hectolitre should be used, rather than the conventional dose of 5–10 grams per hectolitre (Windholtz *et al.*, 2021).

Figure I-8-2. Grapes being harvested mechanically at dawn in the French region of Limoux. © Alain Samson, INRAE.

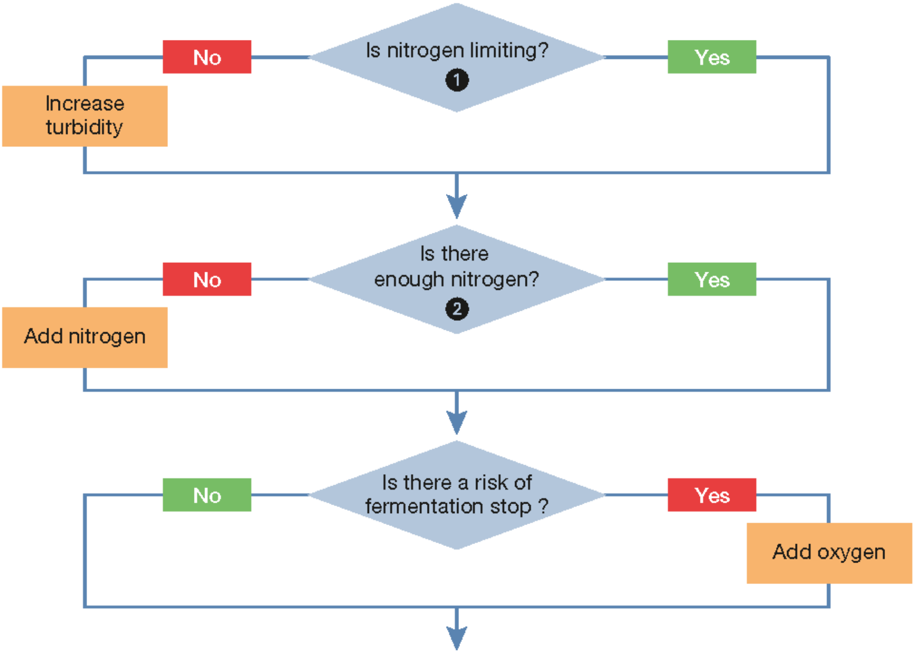
Optimizing wine production

It is essential to manage levels of alcoholic and malolactic fermentation. While much progress has been made in recent years, climate change is affecting grape composition, and the resulting increases in sugar content and decreases in acidity represent an emerging challenge.

Ensuring high-quality fermentation

For fermentation to properly proceed, it is crucial to ensure that yeast nutritional needs are met. It has long been known that assimilable nitrogen, oxygen and lipids (present in solid particles) are the main nutrients required for yeast growth. However, a recent study (Casalta *et al.*, 2021) highlighted that fermentation failure is less likely when yeast nutrition is optimally managed, namely by holistically accounting for interactions among these nutrients. A flow chart has been created to illustrate the proposed approach (figure I-8-3). It is structured as a list of questions: What is the limiting nutrient (a particularly important concern for white and rosé wines)? How much assimilable nitrogen is present in the must, and is it necessary or desirable to add more? What are the risks of fermentation failure when residual sugars are present, given that the likelihood of stoppage is much greater when must sugar content is high? Ultimately, recommendations are situation dependent because the goal is to optimize yeast physiological state during late fermentation.

The above strategy can help winemakers navigate the vast majority of situations. That said, it does not address all potential scenarios, and other approaches are possible. For example, complex nutrients (e.g. inactivated yeast) can be added during rehydration or fermentation, yielding the combined nutritional benefits of nitrogen and lipids. It is also possible to add up to 20 grams of yeast starter per hectolitre, which is another way to promote yeast survival over the course of fermentation. Finally, additional variables



① Nitrogen is the limiting nutrient for yeasts. All assimilable nitrogen will be consumed (up to approximately 400 mg/l).

② There is enough assimilable nitrogen (around 150 mg/l) to ensure a good fermentation kinetic.

Figure I-8-3. Flow chart of nutritional management choices during fermentation. © Jean-Marie Sablayrolles, INRAE.

may have an impact, such as other limiting nutrients (e.g. mineral salts, vitamins) or the presence of inhibitors (e.g. pesticides). Their effects are more difficult to quantify but seem to be relatively minor.

While temperature management systems are ever improving, it is imperative to ensure that temperatures do not climb too high (above 32°C–35°C) when making red wines or dip too low (below 10°C–12°C) when making certain white wines. Of note, current recommendations focus almost exclusively on *Saccharomyces cerevisiae*; thus, they should be expanded to include non-*Saccharomyces* yeasts.

In the longer term, predictive modelling approaches could be used to account for all relevant parameters simultaneously (e.g. fermentation cellar management, refrigeration conditions and quality-related factors) (Mouret *et al.*, 2019).

Limiting alcohol content

Under climate change, a major challenge will be limiting wine alcohol content. Oenological practices have their role to play alongside changes in viticultural strategies and the grape varieties used.

A microbiological approach can be taken, where the goal is to identify yeasts whose fermentation activity generates less ethanol without simultaneously producing more unpleasant aromas. The widely used yeast species *S. cerevisiae* displays limited natural diversity in alcohol production, such that differences never surpass 0.5% alcohol by volume. Without resorting to genetic engineering, several studies have managed to create strains whose metabolic fluxes are partially redirected to overproduce compounds such as carbon dioxide and glycerol. Some can reduce wine ethanol levels by 1% to 1.5% alcohol by volume (ABV) without appreciably affecting oenological properties. Another option is to draw on a greater pool of diversity by employing non-*Saccharomyces* yeasts. This subject is the focus of much research, and it seems likely that even greater reductions in ABV could be achieved (Ivit *et al.*, 2020). However, there are methodological hurdles involved in using such yeasts, especially since they are generally employed in co-cultures or sequential cultures alongside *S. cerevisiae* strains. Indeed, strains may be incompatible because they compete for nutrients or they synthesize compounds that detrimentally affect fermentation.

Physicochemical methods can also be utilized to reduce must sugar content or partially dealcoholize wines. Ultra- and nanofiltration techniques are the main methods used to lower must sugar content. Dealcoholization is generally carried out using membrane-based techniques, namely reverse osmosis and membrane separation (using membrane contactors; figure I-8-4). Vacuum distillation is more frequently used in advanced procedures, such as the production of dealcoholized wines (in France, < 0.5% vol.), a context in which spinning cone column distillation[28] is particularly helpful. Wineries are already employing these methods, given that French wine regulations allow total ABV to be modified by up to 20%. That said, these techniques are rather costly and, although they strive to preserve wine sensory quality, their technological nature is sometimes viewed negatively by winemakers and consumers. In addition, membrane-based methods sometimes diminish wine aroma; research is under way to bring about improvements.

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[28] A two-part technique for vacuum extracting wine volatile compounds, which are then reincorporated after dealcoholization.

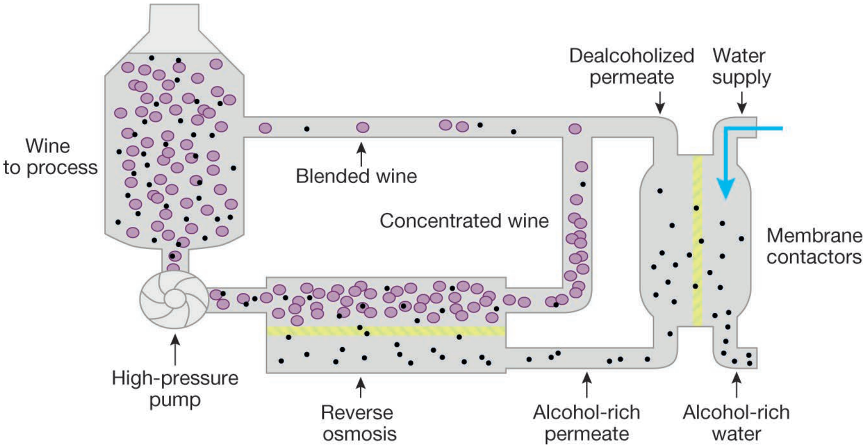

Figure I-8-4. Illustration of a technique for partially dealcoholizing wine using reverse osmosis and membrane separation. Source: Gemstab.

Managing acidity

In many regions, lower must acidity is a significant concern. The typical solution is to add tartaric, lactic or malic acid. While this practice is straightforward, its effectiveness is inconsistent, largely because of precipitation dynamics. Winemakers are allowed to use electromembrane processes, notably electrodialysis, and treatments with ion-exchange resins to reduce pH by as much as 0.3 units. Applied post fermentation, these input-free techniques are more precise. However, the underlying technologies can be expensive and hard to access, which limits their broad-scale utilization. Moreover, French regulations ban their use in organic production systems.

A potential microbiological strategy is to employ acidifying yeasts. Some *S. cerevisiae* strains are able to modulate malic acid synthesis or degradation. For example, researchers recently bred *S. cerevisiae* strains capable of producing up to 3 grams per litre of malic acid (Vion *et al.*, 2023). Some non-*Saccharomyces* yeasts, particularly *Lachancea* species, increase acidity by producing lactic acid, while others such as *Starmerella bacillaris* and *Candida stellata* do so by producing pyruvic or succinic acid (Vicente *et al.*, 2022). As with efforts to limit alcohol content, further research must assess how acidity management strategies affect wine sensory profiles before these microbiological approaches can be more widely integrated into oenological practices.

Extracting polyphenols from grapes

Climate change will affect many grape compounds and will have a particularly strong impact on polyphenols, which play a key role in red wine production. As a result, greater attention must be paid to compound extraction and grape maceration, which may involve adopting new winemaking technologies.

In traditional wine production systems, one solution is to adapt maceration methods (e.g. pressing, pumping over), duration, frequency and timing, as maceration can occur pre or post fermentation. It is also possible to adjust maceration temperatures and employ alternative yeast strains. While extensive research has been carried out on the general effects of these variables as well as on their specific impacts on wine type, winemakers are increasingly confronted with atypical grapes and must adapt their practices accordingly.

Technology-based alternatives to maceration during the pre-fermentation phase include thermovinification and flash release. Enzymes or inputs (e.g. oenological tannins or wood chips) can be used to shape wine quantity, characteristics and sensory properties. These complementary techniques can be employed alongside traditional wine production practices, customizing the maceration process based on grape composition and target wine type.

Preserving aromatic quality

Under climate change, grapes will ripen at higher temperatures, which will alter their composition. Notably, they will contain lower levels of compounds that suffuse wines with the aromas of flowers or ripe fruit, which both convey freshness. In addition, aromas of overripe and cooked fruit will tend to be more perceived. Thus, winemakers should prioritize fermentation methods that exploit microorganisms (yeasts, bacteria) that can better emphasize grape aromatic potential and enhance perceived freshness. Indeed, the aromatic potential of most grape varieties comes to fruition during fermentation, and the choice of yeast strain or species has a particularly important influence in the production of white or rosé wines. In addition, fermentation should occur under controlled temperature conditions (18°C–23°C) to ensure that it proceeds smoothly and to limit the volatilization and degradation of aromatic compounds.

Furthermore, when white grapes ripen during heatwaves, they generally have higher levels of phenolic acids and their esters. During fermentation, *S. cerevisiae* carries out enzymatic decarboxylation of these compounds, generating wine with higher levels of vinylphenols, compounds which contribute to a heavier expression of aromas in wine. To reduce the presence of vinylphenols, winemakers can employ *S. cerevisiae* strains with lower levels of hydroxycinnamate decarboxylase activity when fermenting musts to produce white and rosé wines.

When wine pH increases, storage dynamics are affected. A shift in average wine pH from 3.4 to 3.8 may seem insignificant, but it creates environmental conditions that favour the growth of undesirable yeasts and bacteria. These microorganisms include *Brettanomyces* species, a contaminant yeast, which generate animal odours (horse, stable, leather), and *Lactobacillus* species, which lead to a mousy taste (peanuts, sausage skin). These aromatic issues often go hand in hand with increased levels of volatile acidity (acetic acid). Instances of contamination are growing in number, a trend that cannot solely be explained by unhygienic wine cellar conditions, given that the latter have markedly improved in recent years. It is important to note that the addition of sulfites is an effective way of limit the growth of these unwanted microbes. However, their usage has grown complicated because of the growing appeal of low-sulfite wine and wine without added sulfites for health-related reasons. An additional impediment is that, as wine pH increases, the equilibrium between the different forms of sulfur dioxide shifts away from the unbound form, a more effective antimicrobial agent, and towards bound forms, which display diminished antimicrobial properties. In short, sulfiting is no longer as efficient because of societal expectations around reduced sulfite use and because of increases in wine pH induced by climate change.

Adjusting wine maturation and bottling conditions

White, red and rosé wines made from very ripe or overripe grapes with low levels of acidity are more likely to develop undesirable sensory properties during maturation and ageing. Acidity plays a determinant role in balancing a wine's flavour. At the same time, a wine's degree of acidity will influence the microbial phenomena and chemical reactions taking place.

Weakly acidic wines (i.e. with a higher pH) tend to create an oxidative environment, which more dramatically affects ongoing chemical reactions. The result is a deeper yellow colour, with white and rosé wines displaying a tendency to brown. Such wines also express less aromatic freshness. Ultimately, premature oxidation, or premox, may occur during ageing (see chapter I-4). Thus, wine type must inform maturation duration and methods for dry white, red and rosé wines.

It can be helpful to modify oxygenation levels for red wines by adjusting the proportion of new oak barrels (which are more permeable to oxygen) and by employing inert gas, such as nitrogen and carbon dioxide (most frequently used together). In this way, the wine will be less exposed to atmospheric oxygen during racking and during stabilization or filtration prior to bottling. These precautions are particularly essential in situations where wine maturation involves little to no sulfiting. The antioxidant properties of dry white and rosé wines can be strengthened during maturation by leaving the yeast-lees in contact with the wine (*sur lies*) and by stirring the lees to resuspend them in the wine (*bâtonnage*). Other recommendations include adapting maturation duration and employing inert gas during racking (before stabilization and filtration), as in the case of red wines.

After bottling, closure type and oxygen permeability will influence the preservation of wine freshness or, conversely, affect the emergence of sensory characteristics associated with oxidative ageing (figure I-8-5). Research has found that greater stopper oxygen permeability results in lower levels of free sulfur dioxide and of both fresh and fruity aromas. It also leads to increased levels of aroma compounds that reflect wine oxidation (Vidal and Moutounet, 2007; Pons *et al.*, 2019a and 2019b).

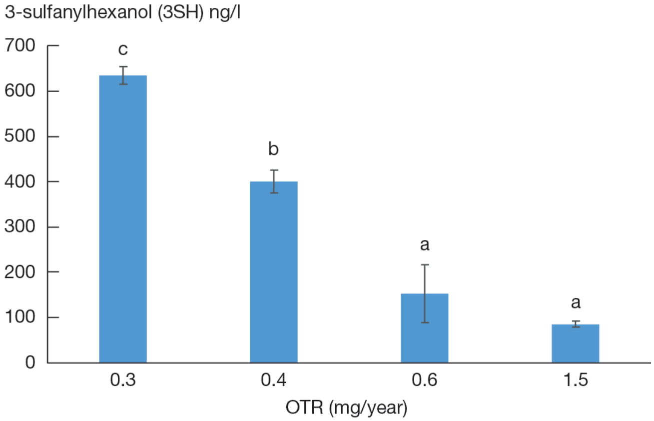

Figure I-8-5. Concentrations of 3-sulfanylhexanol (3SH), a compound that imparts a grapefruit aroma, in Sauvignon Blanc wines after 10 years of bottle ageing as a function of stopper oxygen permeability (oxygen transfer rate [OTR], in milligrams per year). Source: Pons *et al.* (2019a).

Conclusion

Winemakers can adopt various strategies to cope with the effects of climate change on grape composition. Certain techniques are already in use, while others are still being studied. In general, we are moving towards precision oenology, or winemaking practices that are adapted to each set of circumstances. Over the longer term, the objective is not to simply correct problems such as high alcohol content or low acidity but rather to improve understanding of the compounds involved in grape quality, including any shifts undergone during wine production. Ultimately, by drawing on the knowledge gathered in databases, it will become possible to implement strategies far upstream to optimally align viticultural and oenological practices. While societal expectations are increasingly oriented towards lower-input food products, wine production should continue the reasoned use of inputs, whose absence could lead to undesirable sensory shifts in wines.

CHAPTER 9

LEVERAGING REGIONAL CLIMATE VARIABILITY FOR ADAPTATION

Benjamin Bois, Hervé Quénol and Etienne Neethling

Introduction

In this chapter, we will use the geographical term "territory" to specifically refer to a winegrowing area, applying the definition suggested during a seminar held by the LACCAVE project in September 2021 on the consequences of and adaptation to climate change on a regional scale: "A contiguous zone covered by joint decisions and actions on which processes of adapting to climate change are built."

A winegrowing territory as described here is a dynamic concept: its spatial perimeter expands, contracts, breaks up or merges over time, and the joint actions carried out therein evolve according to environmental and socioeconomic contexts. However, the geographical area of the winegrowing territory has a set of physical characteristics (its "physical geography") that are relatively stable or slow to change over time: these include relief, land use, the nature of the soil and subsoil and, to a certain extent, climate. According to the World Meteorological Organization, "climate is the average weather conditions for a particular location over a long period of time". Climate obviously evolves, especially under the impact of contemporary climate change, but its main characteristics (seasonality, spatial variability) are consistent over several years, even decades, because they are largely shaped by a territory's geographical position and relief.

Studying shifts in climate over time and space in a winegrowing territory in a context of climate change requires a multiscale approach (from global to local). Analysing these changes is all the more important given that local climate characteristics (which are highly dependent on the territory's physical characteristics) often determine the specific features of vineyards and the wine they produce (Quénol *et al.*, 2017; Neethling *et al.*, 2019). The scale and objectives of the analysis can considerably shape conclusions about how the environment's physical characteristics influence climate. Climate studies seeking to differentiate winegrowing regions (Champeau *et al.*, 1996; Tonietto and Carbonneau, 2004) will not consider parameters such as soil nature and type, whereas finer-scale climate analyses, such as a "winegrowing terroir study", will have to include the impact of these elements (Neethling *et al.*, 2019).

Take, for example, a winegrowing area of around 12,000 hectares: the Saint-Émilion designation region and its neighbouring "satellite areas" with their appended designations in the Gironde winegrowing region. The soils in this area vary widely, ranging from alkaline to acidic, sandy to clayey, and stony versus non-stony (Van Leeuwen, 1991). The mean annual range of maximum (0.8°C) and minimum (2.5°C) temperatures calculated over an eight-year period is relatively large. For the same grape variety (Merlot), there are spatial differences of 9 days on average in the mid-flowering date and 13 days in the mid-veraison date (de Rességuier *et al.*, 2020). Although the region is not especially hilly, there are significant differences in potential incident radiation (of up to 23% on average per day over the grape ripening period; Bois *et al.*, 2008a). The consequences of climate change will thus differ from one part of this winegrowing area to another. Evaporative demand, which in this region is largely governed by solar radiation (Bois *et al.*, 2008b), is unlikely to have the same impact on grapevine water status depending on the nature of the soil (soil water capacity, rooting capacity, effect of the parent material on the vine's water supply). The sectors most exposed to radiation and with limited soil water capacity (e.g. the limestone rendzina on hilltops; Van Leeuwen, 1991) will likely suffer more from rising temperatures in the coming decades than will the deep alluvial soils of the Dordogne plains. These varying consequences of climate change will require ad hoc adaptation strategies.

This chapter looks at spatial variability in the physical environment of a winegrowing territory and examines methods for characterizing the relationship between regional spatial variability and climate. Then, it explores how this spatial variability can be leveraged for climate change adaptation. After reviewing the scientific approach and the tools used to analyse climate variability in a winegrowing territory, several questions are addressed: How can future climate projections be made at the territory level? How can we assess the expected consequences of these projections for wine production? How can these future climate projections be used to create adaptation strategies?

Assessing the climate variability of a territory in the context of climate change

The advent of geomatics, the exponential increase in digital data storage capacity and the standardization of data exchange methods have resulted in a vast amount of geographical information describing the physical environment of winegrowing territories.

Spatial resolution and the speed of physical environment mapping are benefiting from deeper generalized knowledge of the relief (digital elevation models – DEMs) on a global scale. Space missions such as the Shuttle Radar Topography Mission (SRTM; Van Zyl, 2001) and open access to high-resolution topographic data by France's National Institute of Geographic and Forest Information (IGN) from 2021 have contributed to these knowledge improvements. Depending on the scale being considered, a description of the topographical features of a winegrowing territory can also be quickly produced (Vincent *et al.*, 2014).

Remote sensing and in situ metrology, as well as the automation and miniaturization of devices for measuring and storing climate data since the end of the twentieth century, have led to new methodologies for the spatial analysis of soil and climate. These methodologies are also used to map the physical environment of winegrowing terroirs at different scales. A substantial body of scientific literature on the subject has been produced over the last two decades (see, for example, Quénol, 2014).

The International Organisation of Vine and Wine (OIV) issued a resolution setting out a methodological framework for soil and climate zoning (OIV Guidelines for vitiviniculture zoning methodologies on a soil and climate level, 2012), an updated version of which was proposed by Van Leeuwen and Bois (2018).

Zoning is performed after mapping and draws from relevant criteria to simplify the area and create operational classes for territory-specific diagnostics, decision-making or actions. Climate zoning in a winegrowing area could, for example, divide the area into zones with similar levels of potential early ripening, depending on whether the temperature required for grape ripening builds up over a shorter or longer time frame in the zone (Bois *et al.*, 2018; Gavrilescu *et al.*, 2018). Before starting zoning work, one or more of the objectives for the zoning must be set (e.g. zoning is to be based on potential early ripening or on climate-related risks, whether phytosanitary, frost related or grape-scald related), and the target spatial precision (scale) must be determined. Depending on the selected objectives, the variables of interest and the spatial sampling method may differ. Hail-prone areas can be mapped based on data derived from rainfall radar analysis (Fluck *et al.*, 2021), while air temperature mapping will favour local measurements made using sheltered thermometers (or equivalent devices), coupled with data on the relief (see for example Bois *et al.*, 2018; de Rességuier *et al.*, 2020).

Once the objectives and target spatial precision have been established, a five-step climate mapping and zoning process can be undertaken (figure I-9-1).

The first step (step 1, figure I-9-1) is to collect contextual information on a smaller scale than that of the target zone. When mapping the soil or subsoil, the geomorphological and geological contexts will be important. The types of climate in the study area will be considered and classified using the Köppen-Geiger system (Peel *et al.*, 2007), for instance,

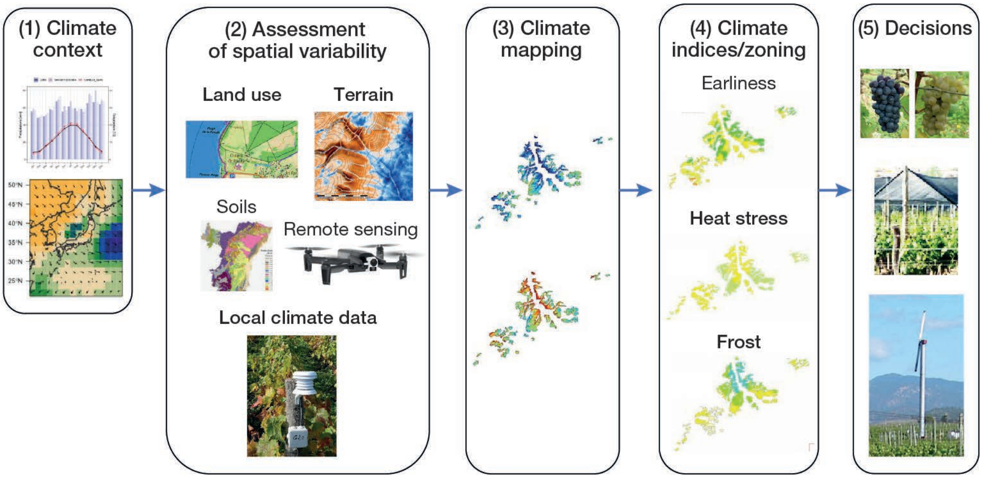

Figure I-9-1. Figure describing climate zoning in the winegrowing industry.

The first step is to **(1)** describe the climate context (atmospheric circulation patterns, centre of action, etc.), which, depending on the specific spatial scale, will be used to identify the geographical elements (latitude, oceans, land masses, relief, land use, etc.) that will affect the spatial distribution of the features to be mapped. The spatial variability of the focal climate variable(s) is then **(2)** measured (via remote sensing, climate measurements from sensors or stations) or inferred when measurements of covariates (soil, topography, etc.) are unavailable. The climate variable(s) (spatial interpolation, remote sensing) are then spatialized **(3)**. The climate variable(s) can be fed into bioclimatic models (before or after the spatialization step) to assess the impact of climate variable(s) relevant to winegrowing. The final steps are to **(4)** identify zones expected to experience similar climate-related consequences for winegrowing (i.e. zoning) to **(5)** support operational decision-making.

or more detailed national-level systems (for France, see Joly *et al.*, 2010). This contextual information provides background on the physical environment and can be used to narrow down key geographical parameters and estimate the expected variability of the climate variable(s) being studied. These insights can guide the choice of an appropriate mapping methodology and potentially adjust the target scale according to the resource constraints (time, human, technical and financial) faced by the zoning process.

The second step involves characterizing the variability and spatial structure of the soil or climate variables being studied. Past research suggests it can prove very useful to perform an analysis of covariates (i.e. ancillary variables), employing digital terrain models and their outputs describing the relief (slope, orientation, etc.), land-use data (water bodies, vegetation, urban areas, etc.), existing soil maps or data from remote-sensing equipment (surface temperature, vegetation indices, soil colour and texture, etc.) (Dobesch *et al.*, 2007; Li and Heap, 2014). These data will be used to construct a sampling plan to identify the relevant spatial positioning of sampling points (sensors or climate stations) and the density of the grid (Hengl, 2006).

In climatology, data collection requires a certain amount of time when sampling involves climate stations (or sensors). To the best of our knowledge, no ad hoc study has been performed to determine the minimum or optimum amount of time to invest in measuring climate variables, so this decision may be informed by the environment, focal variables and desired objectives. Research[29] that used temperature mapping in a natural wine-growing environment produced empirical evidence suggesting that a sampling period of three to six years is long enough to identify frost-prone or potentially early-ripening areas, based on grapevine phenology or grape ripening. Studies at both mesoscales (Bois *et al.*, 2018; Gavrilescu *et al.*, 2018) and local scales (de Rességuier *et al.*, 2020; Le Roux *et al.*, 2017; Quénol, 2014) have shown that the spatial distribution of temperatures is highly consistent from one year to the next due to the key role played by topography (and relief in particular). With regard to precipitation, the sampling time required is likely much longer (i.e. several decades), particularly at local scales, where the spatial distribution of rain fields is inconsistent, especially from one year to the next (Bois *et al.*, 2020).

The third step is to produce maps presenting information that is continuous in space. This spatialization is typically achieved through a process of spatial interpolation, which involves estimating data in space (in this case climate data) in places where measurements have not been performed. This estimation can include environmental covariates (relief, land use, etc.), which often improve the accuracy of the interpolation (Li and Heap, 2014). However, spatial interpolation is not necessary when mapping is based on remote sensing, such as when mapping rainfall (rain radar) or global radiation (Bois *et al.*, 2008a; Pauthier *et al.*, 2016). Regional climate models can also be used to directly produce spatialized climate data. One example is the Weather Research and Forecasting (WRF) model used in New Zealand to produce temperature fields to assess the potential early ripening of grapevines or the risk of spring frost (Sturman *et al.*, 2017).

These digital climate models are often recalibrated or debiased based on climate measurements from a limited number of weather stations; they provide spatialized climate

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[29] Based on the results of the LIFE-ADVICLIM project (High-resolution study of viticultural adaptation and mitigation scenarios, https://www.adviclim.eu/fr), the temperature data acquired at the various pilot sites showed a similar spatial distribution for each growing season.

data that are closer to the measured values. This is the case, for example, with Safran data, which combine various sources, including reanalysis of digital climate simulations (Vidal *et al.*, 2010).

The fourth step involves producing maps of indicators relevant to winegrowing and classifying the area into zones where vineyard analysis or management will be similar.

In agroclimatology, various indices have been proposed, such as the Winkler index to describe potential early ripening (often based on cumulative degree days), the drought index to assess available water resources by including only the climate component, or indices relating to climatic hazards such as the risk of spring frosts, severe winter temperatures or scalding (see, for example, the indicators proposed in the OIV Guidelines for vitiviniculture zoning methodologies on a soil and climate level [2012] or those proposed by Bois *et al.*, 2014). In addition to climate indicators, the dates of key phenological stages (bud break, flowering, etc.) or theoretical grape ripeness can be reasonably well predicted, with prediction errors ranging between a few days and a fortnight, using heat accumulation models of varying complexity (García de Cortázar-Atauri *et al.*, 2009; Parker *et al.*, 2020a). The soil and climate map databases produced can also be fed into more complex agronomic models such as water balance models (Naulleau *et al.*, 2022a) or whole plant models (Brisson *et al.*, 2003).

This step could be used to identify three categories of potential early ripening – early, intermediate or late zones – according to degree days allowing, for each zone, adapted decisions to be taken.

The fifth step is a set of decisions adapted to each different zone identified during step 4.

Constructing future climate projections on a territorial scale

The approach is based on analysing the climate on a territorial scale using networks taking in situ measurements and spatial interpolation of data using geostatistical tools to produce high-spatial-resolution climate maps. The main issue in a context of climate change is to follow this approach by integrating simulations of the future climate on a territorial scale. Most work on the climate adaptability of vines to climate change scenarios is based on data from regional climate models (Hannah *et al.*, 2013; Moriondo *et al.*, 2013; Fraga *et al.*, 2014). Over the last 10 years, enormous progress has been made in refining the spatial resolution of climate projections (now down to a few square kilometres). However, it has not been enough to be able to consider the influence of local parameters (e.g. topography and soil types), even though these parameters clearly influence grapevine and wine characteristics. To produce climate projections on a sufficiently fine scale, the outputs of larger-scale models must be downscaled, which requires methods and tools of varying degrees of complexity.

Downscaling from regional to local scales

As their name suggests, global climate models (GCMs) represent the climate on a planetary scale at a resolution of several tens of kilometres. This means that atmospheric processes and phenomena occurring at a horizontal resolution of under 10 km are not well represented, as these models do not account for fine-scale variation in surface characteristics (such as terrain complexity and land use) or the resulting climate spatial variability. Downscaling methods can factor in the effects of complex surface variability and thus increase the spatial resolution of the models. Two (sometimes complementary) downscaling methods are used.

Dynamic downscaling

With dynamic downscaling, GCM results can be regionalized to smaller subzones of the Earth's surface. This is done using the physical equations associated with atmospheric processes and their interactions with surface characteristics, including terrain and land use. Regional climate models are dynamically downscaled GCMs that regionalize the results of global models using a grid of models of increasing resolution. The first grid is forced to its limits with low-resolution atmospheric fields (derived from GCMs), while the last grid provides simulations at the finest resolution. These fine grids represent atmospheric circulation on a regional scale. The regionalized projections for France are mainly based on dynamic downscaling and produce simulated data every 8 km (Safran grid; Soubeyroux *et al.*, 2021). Several studies have drawn on regionalized climate change projections with finer resolutions to characterize climate spatial variability in winegrowing regions (Sturman *et al.*, 2017; Xu *et al.*, 2012). Dynamic downscaling has the advantage of being based on the same approach as GCMs, in that it attempts to represent actual physical atmospheric processes at the finest possible scale. The drawback is that this approach requires significant computing resources, which makes it difficult to obtain satisfactory results at a very fine scale (resolution of less than 1 km), particularly over long periods (Quénol *et al.*, 2017).

Downscaling using statistical methods

This approach requires less computing capacity, which means it can produce results with a finer level of spatial resolution, making it more suitable for work on a territorial scale. Statistical downscaling involves applying statistical techniques to identify the relationship between a focal climate variable (such as air temperature) and surface characteristics (such as altitude, slope, exposure or surface type). This relationship can be identified using various statistical methods, including multiple linear regression or neural networks. These empirical methods are generally based on climate data obtained from weather station networks. One of their main advantages is that they account for how the characteristics of specific territories influence fine-scale variation in climate while requiring far fewer computing resources. However, one drawback is that they are valid only for the data set from which they were derived.

Integrating fine-scale spatial climate variability into regional climate projections

Statistical methods are particularly appropriate for modelling spatial climate variability on a local scale. When combined with regional climate scenarios (developed via dynamic downscaling), analysis of spatial variability in the local climate makes it possible to refine the spatial resolution of the models and produce future climate projections at a territorial scale. Integrating fine-scale spatial climate variability into climate change scenarios requires a combination of dynamic and statistical modelling methods that use fine-scale spatialized data to force regionalized climate change output data.

This approach to integrating local-scale spatial climate variability into regional climate models was used by the European LIFE-ADVICLIM project. One of the project's aims was to produce future climate projections at the scale of a vineyard field. LIFE-ADVICLIM focused on several vineyards in different European winegrowing regions (Quénol *et al.*, 2014; de Rességuier *et al.*, 2020). Networks of sensors were arranged according to local characteristics and used to acquire air temperature data at each pilot site to generate daily maps (using geostatistical interpolation methods) of spatial temperature variability. Here, the downscaling method was based on the identification of weather patterns using weather type classes. The weather type classes were then associated with spatial models of daily interpolated temperatures. The regionalized EURO-CORDEX output data (12 km resolution) were forced by the local climate model (25 m resolution) for two periods, 2031–2050 and 2081–2100, based on the RCP 4.5 and RCP 8.5 scenarios (figure I-9-2). The climate spatial variability within the pilot sites was similar to, or even exceeded, the temperature increases (degree day sums) between the current period and the 2050 and 2100 time horizons (Quénol and Le Roux, 2021). The results showed that the considerable climate spatial variability due to local effects helped better identify the vineyard sectors where quality winegrowing would be more or less likely under

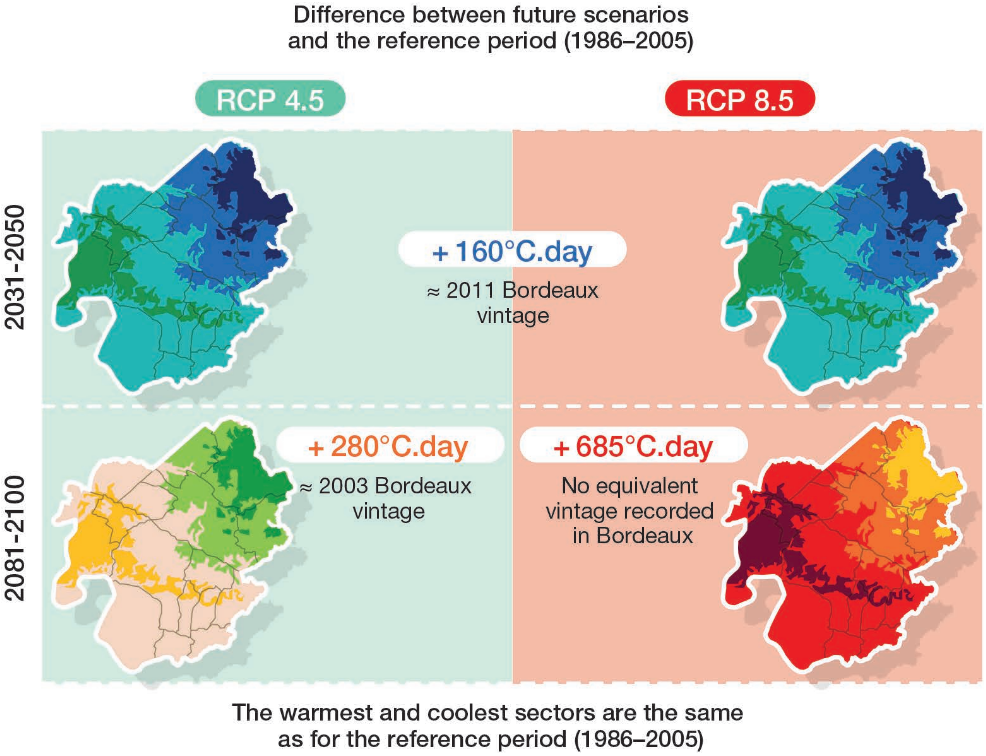

Figure I-9-2. High-spatial-resolution projections of future climate (Huglin index) in Pomerol and Saint-Émilion vineyards for the 2050 and 2100 time horizons based on the RCP 4.5 and RCP 8.5 scenarios. Source: Petitjean *et al.* (2020).

Using these international scenarios, temperature data (EURO-CORDEX) were extracted for the study site at a resolution of 10 km. Downscaling was then applied using a geostatistical model to adapt the climate change projections to the pilot-site scale.

climate change (box I-9-1). However, the main weakness of the statistical approach is that it is a static model that does not take atmospheric physics into account. As such, the assumption is that the statistical relationships defined on the basis of the current climate will remain unchanged in future climates.

Box I-9-1. Case study of Saint-Émilion and Pomerol vineyards

Climate plays an important role in grapevine development, grape composition and wine typicity. It varies from one winegrowing region to another, but local variation can also be substantial. The local scale is particularly appropriate for studying the current and future climate and analysing its impact on winegrowing.

The LIFE-ADVICLIM project studied this parameter by installing 90 temperature sensors over 20,000 ha in the Saint-Émilion and Pomerol regions and their satellite areas. The results showed a high degree of climate variability within this combined zone, with a Huglin index (HI) value of around 284 degree days, resulting in a 25-day gap in ripening. Local-scale maps of temperature and different phenological stages were produced. These data, combined with soil maps, are used as a decision-making tool to guide winegrowers, particularly when choosing planting materials and winegrowing practices.

It is interesting to note that the climate variability measured in the sector was as significant as the recent degree of climate change in Bordeaux. At present, the coolest areas have HI values that match those of the hottest areas 30 years ago. This begs the question as to what will happen tomorrow? Simulations of future temperature and phenology were produced on a local scale. Using these simulations, changes under different scenarios (RCP 4.5 and 8.5) over the medium (2031–2050) and long term (2081–2100) can be quantified. Although the spatial distribution and temperature ranges in this region will not change, the temperature will continue to rise. Regardless of the scenario, in the medium term an increase of 160 degree days in HI is expected, but the trends will be very different by the end of the century. For the RCP 8.5 scenario, an increase of 680 degree days in HI is predicted and will require greater adaptations.

Mitigation, which deals with the causes of climate change, was also considered at field level, by identifying practices with low CO_2 emissions. Practices with the highest emissions (disease management, soil management) were highlighted, as were emission factors such as engine power or the number of operations.

These combined local-scale findings should provide food for thought for the wine industry and policymakers as they consider the adaptation and mitigation measures to implement in the face of climate change.

For more information: https://www-iuem.univ-brest.fr/wapps/letg/adviclim/BDX/EN/#.

Assessing the impact of local climate change by considering winegrowing practices

Once climate projections have been scaled down, how can we translate the consequences for winegrowing in a given territory? The complexity of the task will depend on the established objective. If the aim is to assess specific aspects of winegrowing, such as expected changes in harvest dates or in certain grape composition parameters, agronomic models will be fed with fine-scale projected climate data. In some cases, only fairly simple models should be used. These models may require only a few input variables, such as indicators of early vine ripening (Le Roux, 2017) or combinations of agroclimate indices, such as the average temperature during the growing season and the number of days where the temperature exceeds 35°C and damages the vines (White *et al.*, 2006).

The task becomes more complex when soil, plant, training system, topography and climate characteristics must all be included to study the precise consequences of climate change on grapevine water status: see, for example, the study by Hofmann *et al.* (2022) on the Rheingau and Hessische Bergstraße winegrowing regions in Germany.

Finally, soil and climate differences, as well as various winegrowing practices and wine characteristics, can be included in integrated models. These models can be used to assess changes in yield in order to consider appropriate strategies for the different sectors of a territory (Naulleau *et al.*, 2022a).

A possible shift towards a spatial redistribution of winegrowing areas?

Is it possible to accurately predict shifts in winegrowing geography on the basis of a spatial analysis of climate change's consequences on vineyards at different scales? Many studies have identified new areas where grapes could be grown due to climate change (Fraga *et al.*, 2013; Hannah *et al.*, 2013; Morales-Castilla *et al.*, 2020; Moriondo *et al.*, 2013; Sgubin *et al.*, 2023). At first glance, these are areas where the temperature was not previously high enough to allow the grapes to reach a sufficient level of ripeness. Other climate factors obviously need to be considered (and were in the studies mentioned above), but generally speaking, current and future warming opens the door to winegrowing at higher latitudes and altitudes (box I-9-2).

Box I-9-2. The climate suitability of emerging winegrowing regions: Brittany as a case study

The climate suitability of Brittany for winegrowing was the subject of a study to illustrate a scenario in which a "nomadic" strategy is adopted for adapting viticulture to climate change (Zavlyanova *et al.*, 2023; see chapter II-7). This study led to a new methodology for analysing the temperature potential in emerging winegrowing regions, which utilizes grapevine phenology indices (grapevine flowering veraison – GFV, Parker *et al.*, 2011) and grape maturity indices (grapevine sugar ripeness – GSR, Parker *et al.*, 2020a). This methodology also used cut-off dates for the veraison stage or desired sugar levels to meet different production targets (sparkling or dry wines).

A map of areas in Brittany that are potentially favourable to good ripening of certain grape varieties was created using DRIAS climate projection data for different time horizons and according to different greenhouse gas emission scenarios. The results showed that, looking forward, the temperature conditions in this region appear to be increasingly suitable, depending on the climate scenario, the future time period and wine type (see figure I-9-3). The development of winegrowing in Brittany, made possible by the change in the planting rights regime*, is above all a sign of how much

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climate change is affecting this region. The methodology for analysing climate potential can be replicated in any emerging winegrowing region, with the possibility of adjusting the choice of varieties, timing and target sugar levels to meet the needs of a specific region.

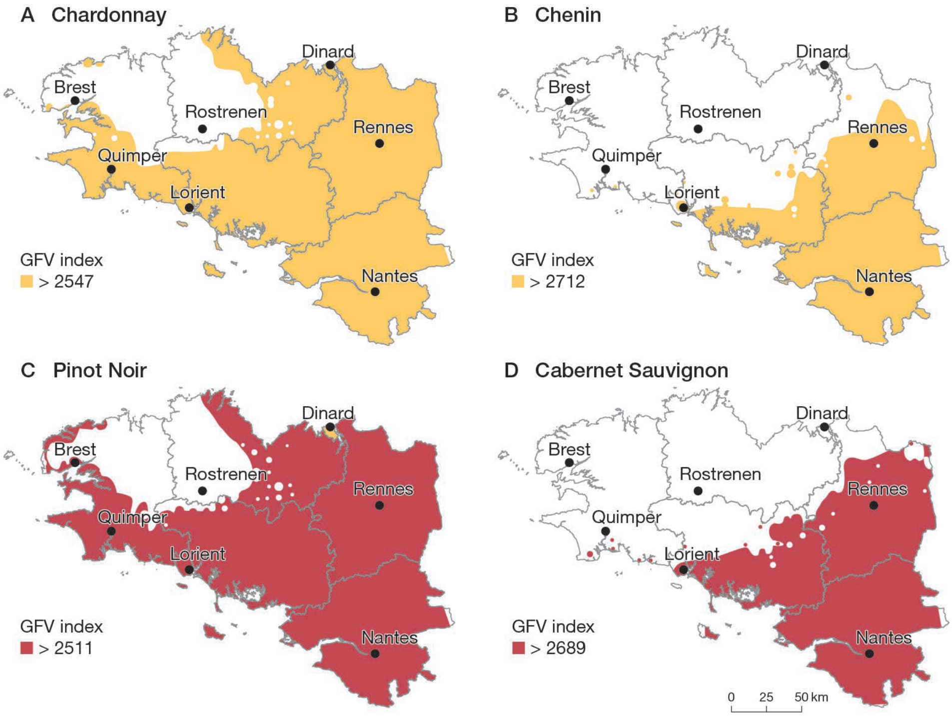

Figure I-9-3. Sectors in Brittany where veraison for four grape varieties (Chardonnay, Chenin, Pinot Noir and Cabernet Sauvignon) would be reached no later than 1 September, on average, by 2031–2060 according to the RCP 4.5 scenario and the CNRM-CM5/RCA4 model. Based on Zavlyanova *et al.* (2023).

* https://www.legifrance.gouv.fr/jorf/jo/2015/12/31/0303.

However, identifying regions where winegrowing will no longer be viable in the coming decades could be more challenging. The first reason is because grapes can be grown under a very wide range of climate conditions (Puga *et al.*, 2022). There is no hard and fast rule that says a climate is too hot or too dry for viticulture – grapes are grown near areas such as the Sonora Desert in Mexico or the Atacama Desert in Chile. Grapevines also boast a level of genetic diversity that could be further exploited as a lever for adaptation (Morales-Castilla *et al.*, 2020), as could the development of new varieties (Delrot *et al.*, 2020). Finally, the industry has shown a strong interest in innovation as a way to address climate change, at least in France (Ollat *et al.*, 2021). It therefore seems risky to predict the disappearance of certain established winegrowing regions. For such predictions to be relevant, it is necessary to adopt a systemic approach, such as the Climate Change Adaptation Framework (CCAF) put forward by Graça and Gishen (2023), which identifies and balances the costs and benefits of climate change adaptation strategies.

Without going so far as to say that the days are numbered for winegrowing, vineyards could lose some of their potential due to climate change. Simulations by Morales-Castilla *et al*. (2020) revealed decreases of between 24% and 85% in current winegrowing areas around the world, depending on the intensity of future warming and the diversification of the grape varieties selected.

On a finer scale, simulations by Moriondo *et al*. (2010) showed an increase in quality potential in areas at altitudes above 600 m until the end of the twenty-first century, but a decline in this potential at lower altitudes by 2050 (box I-9-3). However, this study did not consider spatial variation in soils, which could exacerbate or buffer the effects of climate change at local scales. Few studies have been carried out on spatial and temporal changes in winegrowing potential in response to climate change that considered soil and climate spatial variability. However, Étienne Delay's doctoral thesis (2015) looked at the ways in which stakeholders can create additional value from mountain vineyards in the context of climate change. Few studies have investigated the decline in winegrowing potential and opportunities to relocate vineyards based on local temperature diversity. Work by Naulleau *et al*. (2022a), already cited above, has suggested that relocating vineyards to certain uncultivated fields within the production area would slightly increase production potential. This research is covered in chapter II-6 of this book.

Conclusion

Winegrowing is closely tied to a sense of place, which underscores the potential offered by the natural environment to produce wines with unique qualities. Topographical, climatic, geological and soil characteristics are the foundation of the environments in which grapevines are grown. Landscape features, relief and land use can now generally be described at very fine scales. This is not necessarily the case for soil and climate, whose spatial variability has been minimally considered in studies on climate change impacts and adaptations, notably due to the lack of data. As we have seen, there is a methodological framework for soil and climate mapping, as well as for the downscaling of climate projections. Spatial analysis of these elements suggests that the great diversity of local geographical, soil and climate conditions is a powerful lever for adapting to climate change. All that remains now is to integrate this diversity through systemic analysis to predict the consequences and potential changes in winegrowing areas in response to climate change.

Box I-9-3. The benefits and limitations of moving to higher elevations as an adaptation strategy

In the context of climate change, the scientific community and wine industry professionals are focusing increasing attention on high-elevation vineyards as an adaptation solution (Arias *et al.*, 2022; Figure I-9-4). What constitutes high elevation can vary, ranging from 350 m in the Douro Valley (Portugal) to nearly 3,000 m in China. Under these conditions, the environment is characterized by cooler temperatures (around 6°C lower for each km of elevational gain), but a larger temperature range (around 10°C per km), reduced atmospheric pressure and more global radiative exchange, with a higher proportion of ultraviolet (UV) radiation. The impact on grapevine phenology has been estimated for different grape varieties in Italy's Trento region: there is a delay in harvest date of around 7 days per 100 m of elevational gain, but the effect of global warming on phenological advances is more dramatic at higher elevations (Alikadic *et al.*, 2019). Cooler temperatures can increase frost risk and reduce the overall carbon-assimilation capacity. However, they can also promote slow ripening, acidity and phenolic compound accumulation. UV radiation also affects growth capacity, reduces berry size and has a beneficial effect on the accumulation of antioxidant compounds, monoterpenes and polyphenols. This effect reduces the time lag between the accumulation of sugars and anthocyanins that has been observed when temperatures rise (Martínez-Lüscher *et al.*, 2016). In some vineyards, wind problems can reduce the benefits of higher elevations.

Figure I-9-4. The Tsiakkas vineyards in Cyprus are located between 700 and 1,440 metres above sea level. © Élisa Marguerit, Bordeaux Sciences Agro.

PART 2

Co-constructing strategies for adaptation

CHAPTER 1

WINEGROWERS' PERCEPTION OF AND ADAPTATION TO CLIMATE CHANGE

Etienne Neethling and James Boyer

Introduction

With a focus on producing quality wine, the close relationship between climate and viticulture has always led winegrowers to adjust their practices. From the moment of planting, they will seek a technical itinerary adapted for each vineyard. During the ripening process, they closely monitor berry ripening, then adjusting winemaking practices to best express the potential quality of their fruit. However, across wine regions worldwide, climate change is altering vine phenology and berry composition (Van Leeuwen *et al.*, 2019). Faced with these impacts, winegrowers must once again rethink their vineyard and winemaking practices and strategies. The vine is a perennial plant with generally a lifespan corresponding to two generations of winegrowers, meaning that decisions taken today will have consequences over several decades. In this context, it seems essential to look at how winegrowers are perceiving climate change and its associated impacts. At the same time, understanding how they prioritize climate change adaptation strategies, where technical innovation will play a special role. Based on three surveys conducted in France and abroad as part of the LACCAVE project, we present in this chapter how winegrowers perceive climate change and its observed impacts, then how they foresee adaptation strategies at different temporal and spatial scales, and finally, what may be the determinants of these strategies and innovations.

International perception of climate change and its impacts on viticulture

Winegrowers' perceptions of climate change and its impacts on viticulture have been addressed in the early 2000s, looking at France, Italy and Germany (Battaglini *et al.*, 2009). Considering their beliefs is essential for understanding winegrowers' decisions and assessing the vulnerability and adaptation of their operations. Several studies have subsequently assessed these perceptions at local scales (Lereboullet *et al.*, 2013; Neethling *et al.*, 2017). But to gain a more global view, a survey was carried out in 2019 and 2020 on an international scale as part of the LACCAVE project.

A survey conducted in 18 wine-producing countries

Created using Google Forms, an electronic questionnaire was drawn up and sent to winegrowers in 18 wine-producing countries, accompanied by a message explaining

Figure II-1-1. Number of questionnaires collected for the 18 countries surveyed.

the objectives of the study. To make it easier to understand the questions, the questionnaire was translated into the main language(s) of each country (Argentina, Australia, Austria, Canada, Chile, France, Germany, Great Britain, Greece, Hungary, Italy, Japan, New Zealand, Portugal, South Africa, Spain, Switzerland and USA). Winegrowers were contacted individually and randomly by email or with the help of public bodies and regional associations in newsletters or electronic notifications. The questionnaire was completely anonymous, consisting of 21 closed questions (e.g. perception, observed impacts, priority of adaptation strategies) and 3 open questions (e.g. major issues, climate risks, comments on adaptation), with an estimated response time of 15 minutes to complete. Between 2019 and 2020, 3636 questionnaires were collected (figure II-1-1).

Most winegrowers have noticed a changing climate over the last few decades, regardless of the country considered. Of the total population surveyed, 85% of winegrowers are aware of climate change, with only 4% not noticing any change at all. The level of awareness varies from country to country (figure II-1-2), from 68% in Great Britain to 94% in Germany. In France, 84% of winegrowers have noticed a changing climate, with variations by region, from 76% in Bordeaux to 89% in the Loire Valley.

On an international scale, the most notable changes for winegrowers aware of climate change were the increase in winter and summer temperatures, and the increase in drought. Country-specific modifications were expressed, such as the rise in spring frost events for Austria and Switzerland, hailstorms for Hungary and Italy, winter precipitation for Canada and Great Britain, and summer precipitation for Japan. Specific changes are also perceived between French regions, such as the increase in spring frost events for the Loire Valley and Bordeaux, or that of hailstorms for Bordeaux and Provence. Another survey conducted in 2021 among the defence and management organisms of Nouvelle-Aquitaine confirms these findings (Gouty-Borgès *et al.*, 2022).

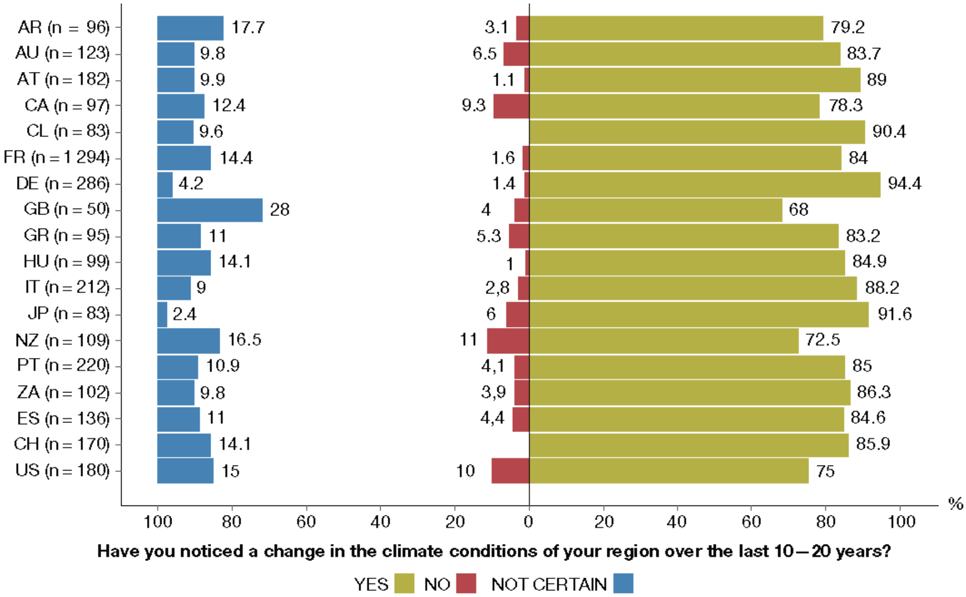

Figure II-1-2. Level of perception of climate change among winegrowers surveyed in the 18 wine-producing countries (n = number of responses).

Impacts perceived everywhere, but vary from country to country and region to region

Winegrowers perceive the impact of climate change on vine performance (table II-1-1). Apart from Canada, many winegrowers from each surveyed country have observed an advance in vine phenological stages, as for instance 85% of the French winegrowers. Climate change is perceived as the cause of a decrease in yields in 10 countries, especially in countries such as Chile (81%) and South Africa (82%), whereas in Great Britain, 67% reported a positive effect on yield. In France, the results show that winegrowers largely perceive lower yields in the Mediterranean regions of Provence (85%) and Languedoc-Roussillon (91%), compared with almost half in the northern regions.

According to the winegrowers surveyed, grape sugar content is the berry component most affected by climate change during ripening. The increase is perceived to be greater in traditional countries such as France (90%), as opposed to New World countries such as New Zealand (41%). Concerning grapevine diseases, the results are much more diverse. Countries such as Hungary, Japan and New Zealand are highlighting an increase in grapevine diseases, while as for countries such as France, winegrowers tend to agree that there is no climate change effect on the presence of diseases. Overall, countries such as Spain highlight the detrimental effects on wine quality, compared to countries such as Great Britain perceiving the beneficial influences. These differences are also apparent in France (figure II-1-3). Climate change

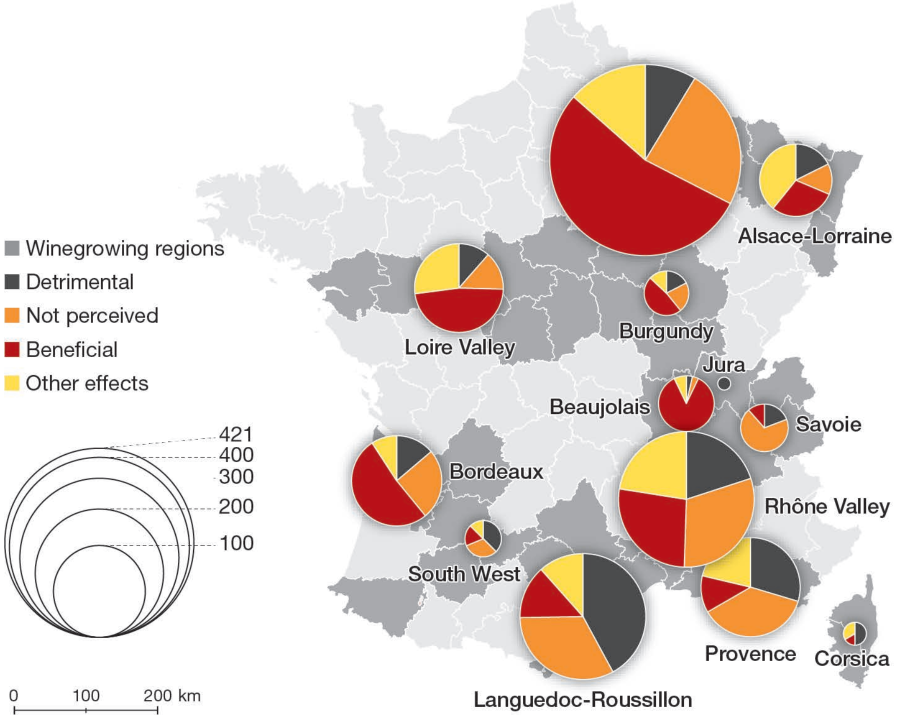

Figure II-1-3. Perception of winegrowers surveyed in France regarding the detrimental or beneficial effects of climate change on wine quality (the size of the circle indicates the number of responses per region).

Table II.1-1. Winegrowers' perception of the impact of climate change on vine performance (n = number of responses). a. Yes, phenology is earlier ↓; no ↔; Yes, phenology is later ↑; b. Yes, yield is lower ↓; no ↔; Yes, yield is higher ↑; c. Yes, sugar levels are lower ↓; no ↔; d· Yes, diseases are fewer ↓; no ↔; Yes, more diseases.

	n	Vine phenology[a] (%)			Grape Yield[b] (%)			Sugar levels[c] (%)			Vine diseases[d] (%)		
		↓	↔	↑	↓	↔	↑	↓	↔	↑	↓	↔	↑
Argentina	76	62	12	26	65	28	8	20	19	61	20	57	23
Australia	99	81	7	12	64	32	4	8	23	68	45	38	17
Austria	160	90	7	3	42	53	5	1	14	84	28	45	27
Canada	76	37	28	36	38	49	13	36	31	33	9	31	60
Chile	75	84	8	8	81	12	7	11	13	76	24	43	33
France	1068	85	5	10	61	29	10	2	7	90	27	43	30
Germany	263	93	2	5	55	37	8	2	4	94	23	42	34
Great Britain	33	73	21	6	6	27	67	9	15	76	21	36	42
Greece	79	66	8	27	51	43	6	15	20	65	9	28	63
Hungary	84	92	2	6	38	55	7	5	13	82	8	20	71
Italy	187	78	9	13	57	40	3	14	20	66	15	36	49
Japan	76	78	21	1	32	65	4	34	47	18	4	22	74
New Zealand	78	73	15	12	25	55	21	10	49	41	8	18	75
Portugal	186	84	6	10	65	28	6	20	18	62	17	26	57
South Africa	88	67	14	19	82	15	3	27	24	49	24	33	43
Spain	113	89	1	11	62	33	5	6	4	89	30	38	32
Switzerland	146	89	7	4	42	50	8	3	10	87	14	43	43
United States	129	55	26	19	27	48	25	25	31	44	7	41	52

appears to be much more beneficial in Champagne (for more than half of winegrowers) than in Languedoc-Roussillon, where its impacts are perceived negatively by 45% of winegrowers. However, a large number of winegrowers express both negative and beneficial effects of climate change, underlining the importance of understanding the different processes and factors that play a role in the local vulnerability of viticulture. For example, warmer summers can be beneficial for viticulture and grape ripening in a northern region such as the Loire Valley, while warmer springs lead to earlier budburst, exposing vines to a greater risk of spring frosts.

Adaptation strategies at different temporal and spatial scales

Almost all the winegrowers surveyed in the various countries (85%) believe that the climate will continue to change over the twenty-first century. However, the priority given to adapting vineyard management practices to expected impacts varies widely from country to country.

Adaptation priorities vary from country to country and region to region

Some countries focus their urgency on perennial practices, such as grape variety selection in Portugal and South Africa, planting location in Spain and the United States, or irrigation systems in Chile and Australia. Other countries, such as Japan and New Zealand, give priority to disease management. Hungary, on the other hand, focuses on grape harvesting practices, while countries such as France and Italy give overall priority to soil management practices. In France, adaptation levers also vary widely from one region to another. For example, winegrowers in Champagne put disease and harvest management first, while in Languedoc-Roussillon the focus is on grape variety and rootstock selection, and irrigation. These results show that several adaptation strategies are possible, depending on the diversity and complexity of the local context.

This diversity of perceptions of adaptation reflects differences in climatic conditions and the characteristics of each vineyard. Contextualized studies of vulnerability to climate change are therefore essential for understanding and considering adaptation strategies at different spatial and temporal scales. This is extremely important in viticulture, as wine quality is closely linked to the specific characteristics of the geographical environment.

A survey of changing practices in the Anjou-Saumur vineyards

As part of the LACCAVE project, another local survey was carried out in 2012 and 2013 in Anjou-Saumur (Neethling *et al.*, 2017). It showed that cultivation practices and viticultural strategies have already changed significantly over the last 30 years, particularly the way soil is maintained between vine rows (inter-rows) (figure II-1-4). In the 1970s, the most common practice was total chemical weeding. Then, in the 1990s, winegrowers progressively adopted permanent grassing for economic reasons or in response to environmental awareness. The practice consisted in maintaining a cover crop in

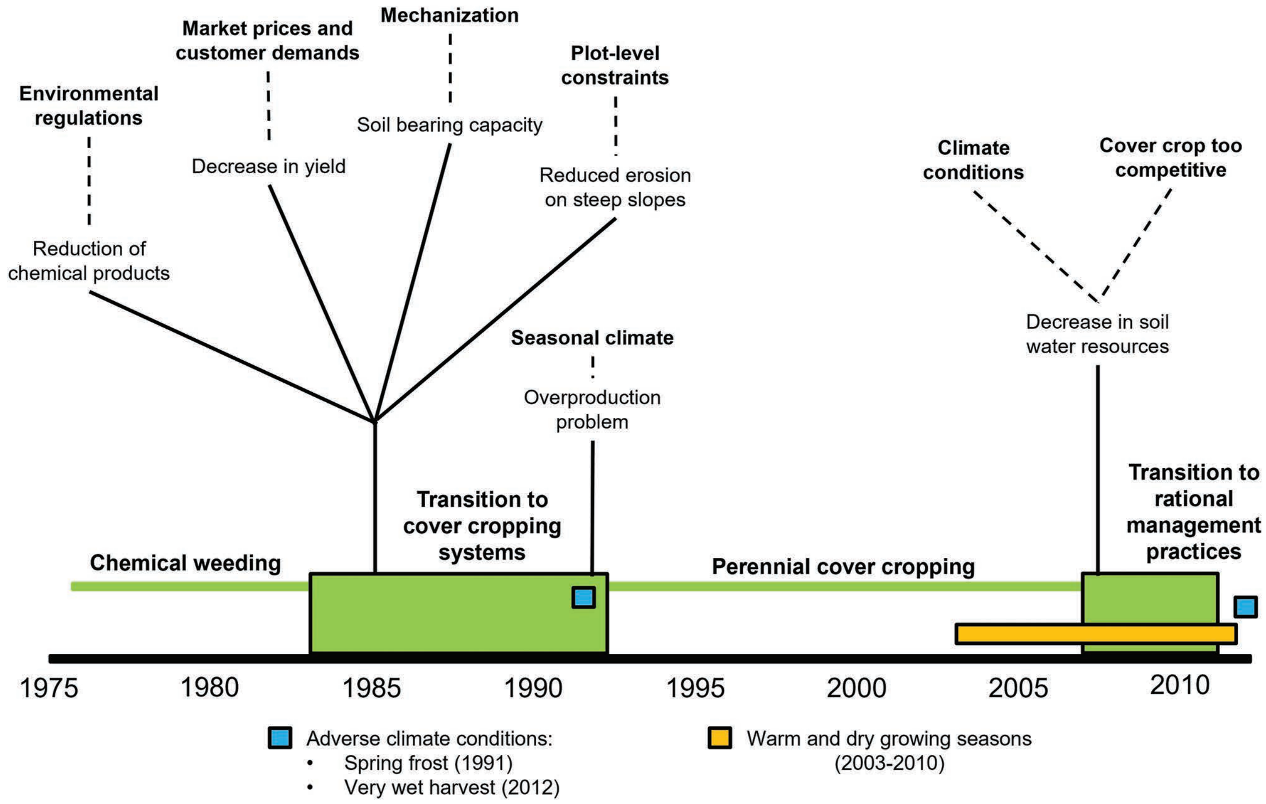

Figure II-1-4. Evolution of soil maintenance in the inter-rows in Anjou-Saumur. Based on Petitjean (2013).

the inter-rows to limit erosion and enable better control of vigour, disease incidence and yield. When vine vigour is controlled and reduced, grapes are richer in sugar and phenolic compounds, with a lower level of acidity (Neethling *et al.*, 2017).

Since the 2000s, the frequency of hot, dry years has increased, and winegrowers in Anjou-Saumur have implemented controlled grassing to adjust the percentage of soil cover and the type of cover to the edaphic conditions of the plot and the year's climatic conditions. This evolution has resulted in better reasoning for the appropriate soil management practices for each plot. This example of the evolution of soil maintenance shows the dynamic nature of cultivation practices and viticultural strategies, and in particular the adaptability of winegrowers, acquired through their experience and knowledge (Neethling *et al.*, 2017). This shows that the climatic factor is regularly considered for adaptation, but that it is not the only one. Winegrowers act on their local environment in a constantly changing socio-economic and regulatory context. Future trends in viticultural practices and strategies will be conditioned by numerous factors, both climatic and non-climatic.

Actions planned for the short, medium and long term

Faced with the current and future impacts of climate change, what adaptation strategies can be implemented at different spatiotemporal scales? Work carried out 10 years ago as part of the LACCAVE project shows that although most Anjou-Saumur winegrowers have noted climate change (Neethling *et al.*, 2017), their perception of its future evolution is marked by a great deal of uncertainty. The adaptations they prioritize mainly concern annual practices: date and time of harvest, transport of grapes to the winery, control of fermentation, phytosanitary protection, soil maintenance, etc. Progress made in recent years in the development of precision mechanical tools greatly facilitates the organization of work to intervene in the most favourable conditions.

Medium-term strategies can be implemented through pruning aimed at modifying the vine's architecture, or through new plantings. The main development in Anjou-Saumur is the choice of rootstock, made possible by a better understanding of soil properties. Long-term strategies, for their part, depend on changes in regulations and are the subject of much debate, although some, such as irrigation, have already found their place in Mediterranean vineyards. Changing grape varieties (or clones) from abroad or from other winegrowing regions favours characteristics such as cycle length, thermal requirements, greater tolerance to water stress, or ripeness achieved at a low to moderate potential alcoholic strength. These grape varieties (or clones) already grown elsewhere benefit from solid references concerning their agronomic behaviour (e.g. Chenin grown in South Africa).

Based on the survey of Anjou-Saumur winegrowers, it is possible to classify adaptation strategies on different timescales (figure II-1-5), bearing in mind that, in detail, they differ according to soil type, plant material and marketing system, hence the interest in studies at local scales. Whether short- or long-term, adaptations also need to be considered on different spatial scales. A winegrower generally owns several plots of vines, which often present a variety of soil and climatic conditions, even on the scale of a small territory. Certain annual practices are therefore not always carried out on all plots at the same time (Barbeau *et al.*, 2015). A winegrowing operation is part of a territory where other winegrowers and other stakeholders concerned by the evolution of practices are present. Certain choices therefore need to be concerted, particularly in the case of cooperative wineries or appellations.

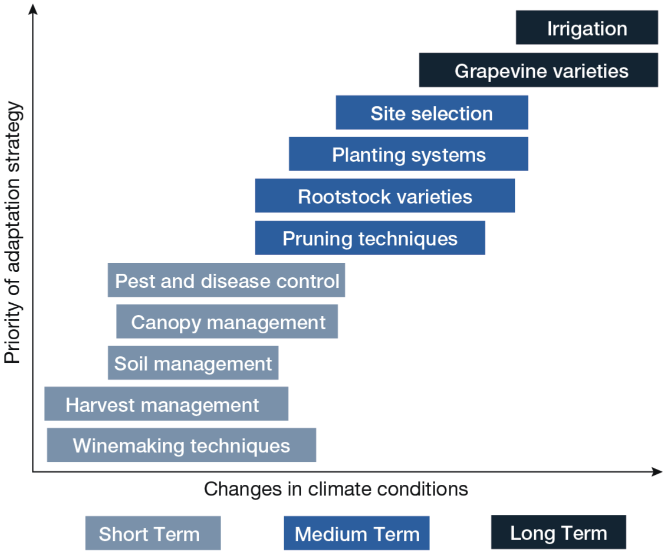

Figure II-1-5. Adaptation strategies considered by winegrowers in Anjou-Saumur in the short, medium and long term, in response to climate change. Source: Neethling *et al.* (2017), adapted from Nicholas and Durham (2012).

However, it is highly likely that, depending on regulatory and environmental constraints, innovations not yet imagined will appear over the next few decades, driving long-term changes in agronomic practices in directions that are difficult to predict today. It is therefore important to question the place of innovations in the adaptation process and to analyse the conditions for their adoption.

Innovation at the heart of winegrowers' adaptation to climate change

Many studies place innovation at the heart of climate change adaptation in different economic sectors (Rodima-Taylor *et al.*, 2012). Innovation refers to the implementation of a new or significantly improved product (good or service) or (production) process, a new marketing method or a new organizational method in a company's practices (OECD, 2005). The challenges of global warming are new and therefore require creativity, both to produce innovations and to integrate them into a production system (Simonet, 2010).

Technical and organizational innovations

Adaptation implies technical or technological change. Drawing on the history of vine and wine and the way this sector has overcome major crises, such as the phylloxera crisis, many believe that winegrowers' adaptation to climate change lies above all in technical innovation (Aigrain *et al.*, 2016b), in various fields that offer solutions (e.g. varietal creations, oenological techniques, drip irrigation and digital) (Ollat *et al.*, 2016b). But these innovations can also be organizational (changes to routines, practices and relationships within the company), institutional (new rules and institutions) or product-related (new wine, for example). They can also be incremental or radical.

The foresight study carried out as part of the LACCAVE project suggests that innovation is seen as decisive for the scenario favoured by winegrowers (see chapter II-7). They want to "innovate in order to stay", because of the investments they have made in their winegrowing region, which impact product quality and reputation. In this context and through interviews with 42 wine organization managers in 7 regions (Boyer, 2016b), the different areas of innovation were specified:

- plant material (rootstocks, grape varieties, clones or hybrids that are later, more tolerant to higher temperatures, more tolerant to drought, produce more acidity and less sugar, etc.)
- vineyard management at plot level, including pruning (more shade for bunches), foliage management (to limit evapotranspiration, etc.), soil management (cover crop or organic amendment) or, more generally, redefining technical itineraries
- management of water constraints on the plot through precision irrigation, agroforestry, landscape design
- oenological operations, with innovations to limit alcohol content (membrane microfiltration, yeast selection, etc.), improve temperature control, reduce the risk of must oxidation, adjust wine acidity and orientate aromatic profiles
- the reorganization of activities and relationships within the winery (work organization, skills) or in its external relationships (warning systems, insurance, consulting, water management, etc.)
- the development of new wines, but also of other agricultural products or services that can seize opportunities linked to climate change or strengthen the company's resilience (diversification in the face of risk, etc.)

These innovations can be either substitutable or complementary. Substitutability occurs, for example, when oenological processes correct the effects of climate change on grape characteristics, up to a certain threshold. Beyond this threshold, a strategy of complementarity is required, combining oenological, viticultural and organizational innovations to cope with the more marked effects of climate change. Hence the need to move beyond an elementary innovation approach to study systemic innovations or innovative winegrowing systems.

Innovations that depend on the trajectories and advisory relationships of winegrowers

The adaptation of winegrowing businesses to climate change therefore depends on vineyard characteristics, but the resources, networks and individual trajectories of winegrowers can also be determining factors, as mentioned in works on issues other than climate change (Chiffoleau, 2005; Compagnone, 2014). A survey of 87 winegrowers producing wines in the Bordeaux, Languedoc and Champagne appellation areas identified the factors influencing their perceptions of climate change and the innovations implemented (Boyer, 2016a; Boyer and Touzard, 2021). These factors may be directly associated with the winegrower and their operation:

- In the three wine regions surveyed, the size (surface area, sales) and economic dynamics of the wineries do not influence winegrowers' perception of climate change, nor their decisions to innovate to adapt. In a context of uncertainty, it is other factors that count.
- The number of years of experience and the level of training of the winegrower play a positive role both in their ability to perceive the effects of climate change

and in their decision to innovate in the face of climate change. The survey shows a learning-by-doing effect, through the construction of references on climate variability and change, necessary to perceive trends or a higher occurrence of climatic events. It also highlights the level of training that can influence a winegrower's openness and ability to integrate scientific knowledge for adaptation.

- Winegrowers who are used to attending trade shows or events related to innovations in the sector are more likely to perceive the effects of climate change than those who do not. This indicator may reflect more difficult-to-analyse individual characteristics, such as curiosity, openness to new ideas or a flair for marketing and communication.
- The winegrower's commitment to organic production is also a factor influencing adaptation decisions, in line with the results of other works, for example in California, which shows that the climate issue is associated with that of the environment, and with a more systemic approach to change (Levy and Lubell, 2018).

But beyond these individual characteristics, the survey reveals that winegrowers' adaptation to climate change is also linked to the relationships they maintain with other actors, organizations and institutions that accompany winegrowing innovation on a national and especially regional scale (Boyer and Touzard, 2021). These relationships are part of an "innovation system" with regional and sectoral components (Cooke *et al.*, 1997; Malerba, 2002). The innovation system concept highlights the role of institutions, networks of players and knowledge bases in innovation processes, alongside internal company factors (see chapter II-3). The survey shows the importance of winegrowers' relationships with innovation system actors, with regional convergences or differences (figure II-1.6):

- In all three wine regions, winegrowers who have advisory relationships with the Chambers of Agriculture or the interprofessional organization, as well as those who take on trainees, declare that they are more committed to adapting to climate change.
- There is also a strong convergence between the winegrowers of the three wine regions, on the one hand to solicit oenological laboratories for solutions to correct the effects of climate change on wine, and on the other hand to solicit their suppliers for the choice of innovative plant material.
- However, there is considerable variation between regions in terms of the actors involved in other areas of innovation.
- In Champagne, links with the interprofessional organization (Comité interprofessionnel du vin champagne) are numerous and predominant. This is the main actor to whom winegrowers say they turn to adapt to climate change, whatever the field of action, except for oenological practices.
- Exchanges of advice between winegrowers play a more important role in the Languedoc vineyards, especially in the areas of vineyard management and plant material.

The institutional framework of each winegrowing region is therefore an important lever for supporting an innovation-based adaptation process. Institutions can reduce uncertainty about the costs of adaptation and the risk of maladaptation, by providing information, standards and a legal framework for the development of innovations. In fact, the wine sector is embedded in a very dense set of institutions, which can lead to a certain rigidity with regard to accentuating the consequences of climate change (Sébillotte *et al.*, 2003). This "institutional framework" (Boyer and Touzard, 2016) operates at different levels, as revealed by the survey: at a local level (unions, cooperatives and PDO specifications); regional level (e.g. ODG, Interprofessions, Chambers of Agriculture, trade shows); national (e.g. INAO) and international (OIV) levels. Research and innovation policies at national (sectoral or otherwise) and regional levels are therefore key to the emergence of innovations and new technologies. Collective action, forms of coordination between players, learning and knowledge-sharing mechanisms, and changes in routines within companies also contribute to creating an environment conducive to adaptation (see chapter II-3).

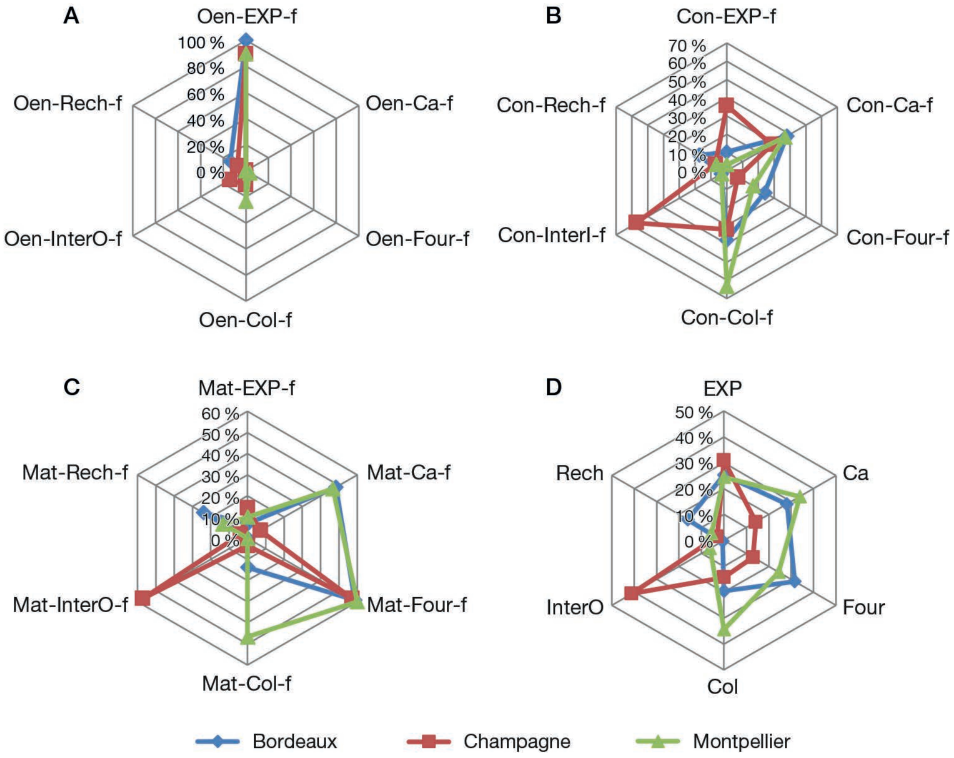

Figure II-1-6. A: actors of the innovation system that winegrowers decide to call upon to innovate in winemaking; B: actors of the innovation system that winegrowers decide to call upon to innovate in vineyard management; C: actors of the innovation system that winegrowers decide to call upon to innovate in vine material; D: perception of the importance of the actors of the innovation system in adaptation to climate change. EXP: oenology laboratories; Rech: research centres and laboratories; Ca: chamber of agriculture; InterO: interprofessions; Four: fertilizers and agrochemicals suppliers; Col: other winegrowers; Oen: winemaking; Mat: vine material; Con: vineyard management. Source: James Boyer (2016).

Conclusion

Here, we focus on winegrowers' perceptions and practices in response to climatic conditions and hazards, as well as the innovations they are implementing to adapt. In 2020, most winegrowers in all the world's vineyards are observing climate change, recognizing changes in temperature and precipitation, and the increase in associated risks.

The impacts observed primarily concern the advancement of phenological stages and certain changes in grape composition, while the effects on yield and disease are spatially more variable. The winegrowers surveyed in 18 countries display a strong conviction that climate change is likely to continue, and plan to change their production systems with different adaptation priorities. Their perceptions and adaptation options need to be contextualized, taking into account not only developments specific to each local or regional vineyard, but also the social, economic and political factors that condition the operation of winegrowing systems.

Innovation is therefore central to the process of adapting to climate change. It enables the development of new technical solutions (plant material, vineyard management, oenology) to correct or anticipate the effects of climate change on wine production and quality, but it also concerns new practices and relationships within wine companies and their territories (particularly AOC). At a time when new adaptation strategies are being developed, with many uncertainties, an analysis of the factors influencing innovation shows the importance of winegrowers' individual motivations and trajectories, but also of the advisory or collaborative relationships they build within an innovation system, above all on a local and regional scale (see chapter II-3).

CHAPTER 2

IS THE MARKET READY FOR WINES AFFECTED BY GLOBAL WARMING?

Éric Giraud-Héraud, Alejandro Fuentes Espinoza, Alexandre Pons, Sophie Tempère and Stéphanie Pérès

Introduction

Changes to the climate can have a major impact on grapevine physiology and the characteristics of the wines they produce. As a general rule, high temperatures over prolonged periods can lead to early ripening and even overripeness, causing an increase in sugar content and altering aromas and flavour. Wines made from grapes with these characteristics are generally higher in alcohol and lower in acidity (Webb *et al.*, 2008; De Orduña, 2010). Red wines, for example, are typically characterized by hints of jammy fruit (Pons *et al.*, 2017; Allamy *et al.*, 2018), recalling the traditional aromatic expression of wines made in latitudes that are warmer and drier than winegrowing areas in temperate zones. This hypothesis has also been put forward by a number of authors who believe that the "generally desirable sensory qualities" of wine, namely colour, aromas and taste, will be altered by global warming. (Duchêne *et al.*, 2010; González-Barreiro *et al.*, 2014).

Economists will argue that the changes in wine characteristics brought about by global warming could lead to welcome developments in some markets. Many observers have pointed out that the wines now produced in many winegrowing regions have never been of such good quality or so balanced. What is more, certain growing practices, such as extreme leaf removal around the fruit zone or early harvesting, are in fact used to encourage the fruit to ripen and accentuate hints of jammy fruit (Van Leeuwen *et al.*, 2022a). The effects are similar to those caused by global warming, although these wines are produced specifically with the intention of fulfilling consumer expectations. The fact that wines made from overripe fruit have long been on the shelves shows that they meet consumer expectations, or at least met them to some extent or other. Ultimately, global warming could actually be a boon for some producers and for entire winegrowing regions even.

However, what was once a production choice has now become a constraint that winemakers have to work with. Global warming has resulted in a loss of strategic flexibility that could prove dangerous if market demand should move in the opposite direction. In this chapter, we put forward this particular viewpoint, using an experimental market to gauge the effects of consumer fatigue. The key point we wish to raise is that of what has become known in France as "redemande[30]", or repurchase intention.

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[30] It is at this point that we would like to pay tribute to Jacques Puisais, from whom we borrowed this expression ("redemande") and gave it an economic slant. The aspect of consumers going back to buy the same wine is all too rarely considered in consumer surveys, despite the fact it is the very foundation of the long-term desirability a product or brand.

Assessing this metric involves checking whether or not the expectations expressed by consumers at a given moment remain stable over time.

In our experience, the spontaneous responses and impulse buying prompted by this very type of wine among consumers puts the consequences of global warming in a different light, even if this demand has shown to be inconsistent over time. In fact, we show that customer fatigue can set in after initial appreciation for a product, and how this translates into a reduced willingness to buy and, in short, a fall in value of products that were initially thought to have a high market value. When the market is likely to involve repeat purchases, an outcome such as this can be crucial and have unexpected yet visible economic effects when sales trends are tracked.

An experimental study for measuring consumer preferences

Let's return to the issue at hand. What type of wines will be in demand with consumers in the future? Given changing tastes, uses and consumption patterns for a product that is not a basic necessity, this is not an easy question to answer at this moment in time. It goes without saying that environmental issues and the huge demand for natural products have all had their effect, as they have across the food and drink market as a whole (Pérès *et al.*, 2020; Raineau *et al.*, 2023). But societal expectations are no more important than sensory considerations – far from it. Consumer habits, which are not strictly the same thing as tastes, also vary widely around the world, making it unwise to generalize. If we keep these things in mind, it is possible to gather results from experimental procedures that can easily be replicated across different geographical areas, all with a view to making comparisons and, ultimately, to map out consumer preferences/choices based on sociocultural backgrounds and consumer habits.

Combining sensory analysis and an experimental auction procedure

The experimental design we proposed for the Nouvelle-Aquitaine region was also published by Fuentes Espinoza (2016) and Tempère *et al.* (2019). In conducting this research, we used a methodology that combined sensory analysis and gathered expert and consumer appraisals of different wines, based on the characteristics described above, and an experimental auction procedure which, following the example of Lusk and Shogren (2007), provides a better understanding of consumer purchase intention. The aim was to identify the maximum purchase price for a wine, i.e. the price above which consumers would refuse to buy at a given moment. This maximum price, commonly known as "willingness to pay" (WTP), is a value specific to each consumer, unlike the market price, which applies to everyone. Consumer WTP depends, of course, on sociodemographic factors and disposable income, not to mention impulse buying and the material ability to purchase the product. Nevertheless, in comparing the WTPs identified for different wines with different sensory profiles and where different information is available on these wines, we can gauge genuine market expectations. In the main, we focused on the effect of sensory attributes.

Selecting of wines (laboratory evaluation by a group of experts)

Three red wines (A, B and C) from the same PDO in the Bordeaux region were selected, all from the same 2010 vintage (a warm vintage, chosen for the general quality of all Bordeaux-designation wines). Although they belonged to the same PDO (a well-defined area in the Bordeaux region), the wines were very different in character, in keeping with the attributes mentioned above in relation to the consequences of global warming. Firstly, the ethanol content of the wines ranged from 13.9% vol. (Wine A in our experiment) to 15.2% (Wine B in our experiment), with Wine C, which had an ethanol content of 14.4%, in between. As shown in figure II-2-1, Wine A had the lowest intensity of cooked/jammy fruit, while Wine B had the highest intensity and Wine C a medium level of intensity. Finally, an atypical Wine A′ was made by adding ethanol to Wine A until it matched the ethanol content of Wine B, the aim being to check whether our results could be explained solely by the volume of alcohol the wines contained.

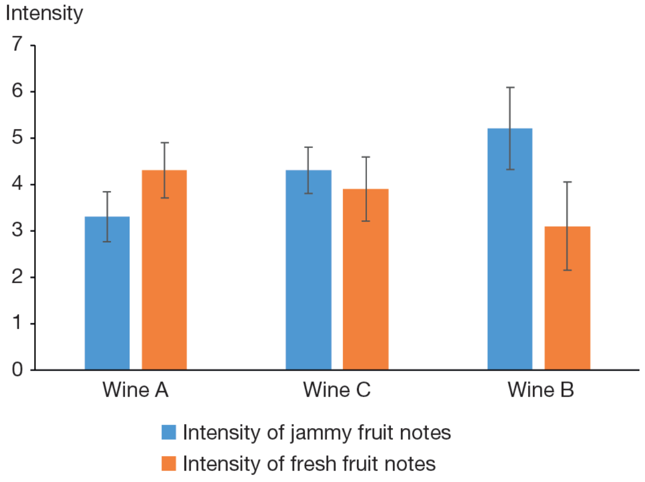

Figure II-2-1. Average intensity of jammy and fresh fruit notes obtained from the red wines selected. Source: Tempère *et al.* (2019).

Consumer recruitment

Nearly 200 consumers from the Gironde area were approached, based on their consumption and regular purchase of 75 cl bottles of Bordeaux wines retailing at over €15. We split these consumers into two groups, G1 and G2, which were roughly the same in terms of age, gender, social grades, and consumption habits and frequency. Both groups were subject to the same experiment protocol in the laboratory. Group G2 was much more familiar with "extreme" wines A and B, however, having had had the opportunity to drink them over a period of three days prior to the experiment. Each day, the consumers in this group were asked to test the two wines provided to them beforehand and to rate them, using only the reference A or B on the label. At no time were the consumers in Group G2 told that wines A and B were also included in the lab experiment. However, unlike Group G1, they had been given plenty of time to form a more informed opinion about the extreme wines at the centre of our experimental study.

Experiment protocol

We recruited a large and diverse group of consumers covering a sufficiently wide range of sociodemographic characteristics. As part of the experimental market, they were required to state their WTP for each wine according to an incentive procedure.[31] At no point during the experiment was the retail price nor the identity of the wines revealed to consumers, apart from the vintage and region of origin.

A total of 184 consumers followed the experiment protocol in return for payment for their participation (they were recruited by a company specializing in the field). With 92 participants in each group, four sessions involving 22 to 28 consumers were needed for each of groups G1 and G2. The consumers provided a WTP for each wine when tasting blind and were then able to change this WTP during the visual, olfactory and gustatory phases.

The tasting phases were as follows:

- **Phase 0 (background information):** provision of information common to the four wines and relating to the name of the PDO selected and the vintage (2010)
- **Phase 1 (visual):** simultaneous evaluation of the colour of all four wines
- **Phase 2 (olfactory):** simultaneous evaluation of the bouquet of all four wines
- **Phase 3 (gustatory):** simultaneous evaluation of the taste of all four wines
- **Phase 4 (alcohol content information):** information on the exact alcohol content of each of the four wines

The experiment protocol is increasingly informative in nature, with our approach being to follow, as closely as possible, the customary order in which the characteristics of wines are experienced, all in accordance with the objectives of our experiment. In each phase, consumers stated and were free to change their WTP for each wine, taking into account the additional information given in that phase.

Experiment results for both groups of consumers

As the aim of the experiment was to measure changes in WTP rather than its absolute level at any given time, we standardized the WTP obtained in the first phase of the experiment at 100. At this initial stage, there was no difference between the wines, as the information pertaining to them was identical. Figure II-2-2 shows the change in average WTP for the four wines and for both consumer groups, G1 and G2.

In G1, Wine B was clearly preferred to Wine A. The Friedman test, which is non-parametric, reveals a preference for Wine B over Wine A, with a significance level of 5% for Phase 3 (gustatory) and Phase 4 (information on alcohol content). Wine C (medium intensity) had an average WTP between Wine A and B. In contrast, the "atypical" Wine A′ has the lowest average WTP. The difference with Wine A is not significant, however. The "atypical" Wine A′ thus remains in the competitive range, and its introduction on the market is not out of the question.

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[31] We used the BDM mechanism (named after Becker, DeGroot and Marschak, 1964) to identify the consumers' WTPs for each wine. The use of this mechanism avoids the declarative bias associated with conventional surveys.

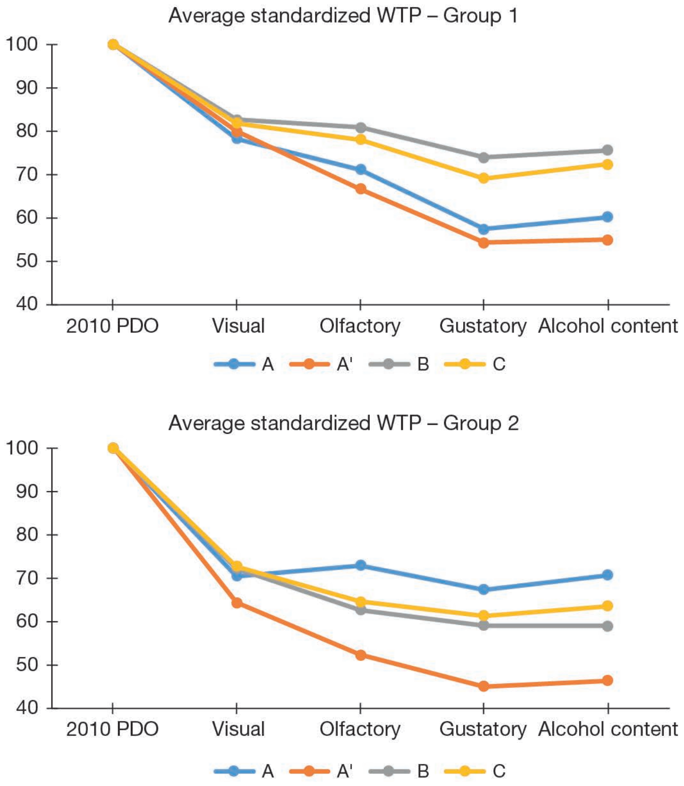

Figure II-2-2. Average standardized willingness to pay (WTP) by wine and by phase for consumer groups G1 and G2. Source: Tempère *et al.* (2019).

But we can see how this change in WTP in G1 can be challenged to a large extent by G2, where the participants had had the opportunity to familiarize themselves with the wines beforehand. While the general trend in WTP is similar for the second series of curves, there is also a reversal in WTP, with a marked preference for Wine A over Wine B in the "olfactory" and "alcohol content information" phases. Wine C again recorded a WTP between wines A and B, while the "atypical" Wine A was then regarded as significantly inferior to all the other wines. The atypical wine was then "removed" from the market, which demonstrated how discerning consumers are when it comes to paying and not just evaluating.

However, the key point to make here is that this switch in preference between Wine A and Wine B is not linked to a better appreciation of Wine A in one group as opposed to the other. The WTP for Wine A only varied by 6% between the two groups, which is not significant. In contrast, there was a loss of interest in Wine B, which saw its WTP decline by more than 20% across groups G1 and G2. It should be noted that this loss of interest, measured here in the last phase of the protocol, can be perceived from the olfactory stage of the experiment onwards.

The question here is whether consumer preference has truly changed. In anticipation of this risk, we carried out a additional survey with participants on their genuine perception and appreciation of characteristics directly influenced by global warming. It is especially notable that while 63% of them liked Wine B, precisely because of its jammy fruit character, in Group G2 only 39% gave a positive response to the same question. Ultimately, what we have here is the highlighting of the ability of consumers to taste wines and differentiate between them (Owen and Machamer, 1979), bearing in mind that the skill of recognizing wines can be acquired through passive perceptual learning, which is in line with the subconscious phenomenon observed by Hughson and Boakes (2009) in particular.

Learnings from the experiment

This experiment may reflect the market's assessment of the characteristics of wines produced under the same PDO and which can be influenced by global warming. Our working hypothesis was that these characteristics would be similar to those observed over several years with certain wines intentionally produced to meet "current" market demand. As such, we have demonstrated the weakness of judgments made on the basis of short-term preferences, which is very often the case in standard assessments, professional tastings or opinion surveys published in the media, which often portray themselves as purveyors of quality.

Wines affected by climate change and the risk of consumer fatigue

Our findings of perceived quality using WTP as a criterion shows how consumer fatigue can influence repeat purchases. The risk and economic impact that global warming poses to consumption is largely due, therefore, to a gradual market shift away from a style of wine that no longer holds any appeal. It would also be worthwhile to draw parallels with other markets, such as low-alcohol and non-alcoholic beverages, where ranges have grown in size. The replacement of wine with beer, the development of tea-based drinks and alcohol-free wines, among other changes, are all signs that should cause us to ponder the disaffection shown by a number of wine consumers (see recent research by Čiderová and Ščasný, 2022). Overly concentrated wines are one possible reason for the sharp decline in the red wine market in some countries, not to mention a lack of freshness and alcohol levels that have become too high and unpalatable for many consumers. Generally speaking, rosé and white wines are less affected by the economic crisis currently besetting the French market than red wines (FranceAgriMer, 2022).

The influence of the consumption of other beverages

It should also be pointed out that the hedonic ratings provided at the gustatory stage were compared with the frequency of consumption of other beverages (fruit juices, soft drinks, flavoured wines, fortified wines and spirits). The only notable effect observed was that of the frequency of consumption of fizzy drinks on the evaluations of Wine B in our experiment, with its aromas of jammy fruit. Participants consuming fizzy drinks once a week or more enjoyed Wine B more (95% certainty that the rating for Wine B in this group is between 5.1 and 6.7 out of 10) than those who consumed them less often (95% certainty that the rating for Wine B in this group is between 4.3 and 5.3 out of 10). Furthermore, consumers who drank fizzy drinks most often demonstrated a clear and significant preference for Wine B over Wine A (95% certainty that the rating for Wine A in this group is 3.7 and 5.5 out of 10).

Evaluating consumer preferences in terms of innovations in adaptation

We also need to assess the level of confidence in innovations designed to make it easier to adapt to changing consumer tastes. In agronomic terms, the possibilities are real but have yet to be fully exploited. It should be remembered that all agronomic developments through till the end of the twentieth century focused on enhancing fruit ripeness (leaf management, row orientation, green harvesting, etc.). It seems natural just to undo what we have patiently built, to redirect our knowledge in a climate context that is the reverse of what the generation before us faced. We can also rightly wonder whether this "sustainable" option would not make more sense than solutions that are more technical in nature but less in keeping with high-quality production and current corporate social responsibility requirements. For example, more precise management of the grass cover, canopy management and, in general terms, the level of grape ripeness can help shape this development, which undermines lasting appreciation of red wines made in Bordeaux (see chapter I-7).

In terms of winemaking, the choice of yeasts can be a lever for action, implemented in conjunction with more common and invasive acidification or even dealcoholization techniques (see chapter I-8). Although vineyard management is ethical and more in line with development of the terroir, it should be said that these winemaking techniques are being used more and more extensively around the world in a bid to offset the effects of global warming in affected regions. To this end, in another project (Fuentes Espinoza, 2016) we studied innovation in the "partial reduction in alcohol content" in red wines and in "acidification" in rosé wines. For the latter, we tested two wines: a control Wine D and an acidified Wine E, which had a lower pH. To make Wine E, Wine D was subjected to the acidification process. We tested three red wines: a control Wine F with an alcohol content of 14% vol., a Wine G at 12% vol. and a Wine H at 10% vol. Wines G and H were made from Wine F following a partial reduction in alcohol content of 2% and 4% vol., respectively.

Table II-2-1. Acidity and alcohol percentage of the wines tested. Source: Fuentes Espinoza, 2016.

pH		Alcohol content		
Rosé wines		Red wines		
Wine D (control)	Wine E (acidified)	Wine D (control)	Wine G (dealcoholised)	Wine H (dealcoholised)
3.57	3.41	14% vol.	12% vol.	10% vol.

Although, generally speaking, there was a preference for the control wines (free of innovation) in terms of WTP and organoleptic perception (hedonic ratings) over the wines made from the two innovations being tested, the differences are not significant and the results can be interpreted as revealing a lack of preference. An initial interpretation would be that, in relation to alcohol and acidity, consumers are unable to distinguish between the control wine and the wine made using the innovation, in line with results encountered by many authors (Lisanti *et al.*, 2011; Escudier *et al.*, 2014). However, we can conclude from a more detailed analysis by sociodemographic characteristics that some groups of consumers have clearly defined preferences.[32] The wines tested (control and modified)

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[32] Analysis of variance, with a pairwise comparison using a Duncan test ($p < 0.05$), confirms this result, with highly significant differences between consumers' first and second choices.

are thus perceived differently during sensory evaluation. These results, which come from the analysis of individual preferences and by sociodemographic characteristics, suggest that the innovations tested may be accepted by some of the consumers only.

Conclusion

In this chapter, we addressed how global warming may require adaptations in winegrowing, focusing on the gap between supply and demand on the wine market. The issue of the characteristics of products offered to consumers in the future seems to us to be crucial, because the change in tastes seems diametrically opposed to the "natural" development of wine traits. This raises the question as to whether consumer disaffection has moved from risk to reality. In other words, we believe that the disaffection with "wine" as a product witnessed in France and many Mediterranean countries for several years now has as much to do with these organoleptic shortcomings as with the health and environmental issues often cited by industry observers.

We are also of the opinion that sensory analyses do not pay enough attention to the consumer fatigue discussed here. The concept of repurchase intention is, however, an economic issue that needs to be considered when anticipating the ideal characteristics of future wines, bearing in mind that the term implies, above all, regular acceptance of a retail price, provided that it is relatively stable. In short, it is about a lasting willingness to pay.

Innovations in winemaking and agronomy, or simply a return to better-oriented production systems, will no doubt allow winegrowers to address the adverse effects of global warming on wine characteristics. More radical solutions, such as relocating vineyards, will surely pose other problems in terms of sensory suitability. Here again, we need to ensure that these innovations have the genuine approval of the market, while taking into account the ever-increasing demand for natural wines on the part of consumers, although this ill-defined term should be used with the utmost caution.

Readers will notice that throughout this chapter we have chosen to use the term "global warming" instead of "climate change". We have focused on effects directly linked to rising temperatures rather than on production variability, which could also have significant economic consequences, but in an entirely different way. The vagaries of supply are causing problems in terms of getting products onto the market, as well as building brands and marketing them. These difficulties need to be analysed and addressed.

CHAPTER 3

SUPPORTING FRENCH VITICULTURE THROUGH THE CREATION OF "ADAPTATION ECOSYSTEMS"

James Boyer and Jean-Marc Touzard

Introduction

If wine producers are to adapt to the climate crisis in the long term, they will have to rethink their production systems, combine varietal and technical innovations, and embrace organizational changes and new spatial strategies that may even involve relocating part of their vineyard (Ollat *et al.*, 2016b). Change of this scale is not the sole responsibility of individual companies, however. They depend on knowledge and resources that are deployed through interactions between wine industry stakeholders, between winegrowing areas and regions, and within society as a whole. Study of the adaptation of winegrowing areas requires taking into account these interactions, networks and the knowledge they draw on or produce, and the institutions that can organize them at different scales, from local to international.

Collective aspects such as these are a focal point of social sciences research into innovation. They can be acted on jointly through innovation systems, which can be national, sectoral or regional,[33] and through clusters, which are focused more on companies operating in the same industry and in close geographical proximity to each other (Porter, 1998). Work focusing on such concepts has been carried out already in the wine industry, in particular in analysing the role innovation has played in making vineyards outside of traditional winegrowing areas in Europe competitive (Porter and Bond, 1999; Giuliani *et al.*, 2010). One of the challenges of the research conducted as part of the LACCAVE project involved adopting these approaches to gain a better understanding of how French winegrowing areas are adapting to climate change, and more specifically the role of research in this area (Boyer and Touzard, 2016 and 2021). In this chapter, we review the work carried out on innovation systems and clusters in the viticulture and wine industry, and then present the multiscale approach developed as part of the LACCAVE project to analyse the collective dimensions of climate actions in winegrowing areas. This research reveals the importance of the relationships built up at regional level between winegrowers, wine trade associations, and research and training bodies, foreshadowing the development of "climate change adaptation ecosystems".

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[33] An innovation system can be defined as a set of stakeholders, organizations, institutions and networks that promote the creation of new knowledge and innovation in a given geographical area or industry (Touzard *et al.*, 2015).

The climate issue in the analysis of viticulture and wine innovation systems

Our analysis of the collective and institutional dimensions of climate change adaptation in French vineyards is an extension of earlier research that revealed the role of innovation systems in the competitiveness of non-European vineyards. We propose revamping this analytical framework through the concept of adaptation ecosystem.

Regional innovation systems and clusters: new factors in the competitiveness of winegrowing regions?

In France, research into innovation in the viticulture and wine industry has long focused on two avenues: firstly, nationwide approaches that point to the importance of industry regulation, policies and institutions providing standards regulating wine quality and a framework for innovation and research into viticulture and wine (Boulet and Bartoli, 1989; Sébillotte *et al*, 2003; Hannin *et al*., 2010); and secondly, studies at local level on the adoption of innovations by winegrowers, taking into account their professional networks and the role of organizations such as appellation associations and cooperative wineries (Compagnone, 2014; Chiffoleau and Touzard, 2014).

However, the strong growth of winegrowing areas outside Europe from the mid-1980s onwards gave rise to new questions and approaches, in keeping with the work being done in other industries on the territorial dynamics of innovation, regional innovation systems and clusters (Etzkowitz and Leydesdorff, 2000). The speedy development of these "new" winegrowing areas was not only linked to lower production costs and foreign investment but also innovation, which was boosted by regional cooperative links between wine companies, industry organizations, and universities and research centres (Giuliani and Bell, 2005). The University of California, Davis in the United States, Stellenbosch University in South Africa and the University of Adelaide in Australia have played a key role in various "wine clusters" (Porter and Bond, 1999), where new engineers, technicians and wine traders are trained, knowledge tailored to local production conditions is acquired, an entrepreneurial and innovative wine culture is developed, and links with other research and training centres around the world are established, including Bordeaux, Montpellier and Dijon (Touzard and Hannin, 2023). In a globalized wine economy, competitiveness is thus a long-term issue for regions that organize themselves, promote innovation and training, and set up local and international cooperation networks.

Reflecting this work on clusters in non-European winegrowing areas, research conducted in France – including the LACCAVE project – has identified the characteristics of regional viticulture and wine innovation systems, analysed their effects on the competitiveness of French winegrowing areas, and looked at the way in which they can respond to new climate challenges and help winegrowers implement adaptation (Boyer and Touzard, 2016).

Including climate issues in the analysis of innovation ecosystems

Studies on wine clusters in both "old" and "new" wine-producing countries have gradually taken into account issues other than economic growth and the strengthening of market positions. Current research looks at the organizational, relational and cognitive conditions that support adaptation to challenges such as environmental protection or climate change, in particular in California (Levy and Lubell, 2018), Australia (Ratten, 2018) and Italy (Chaminade and Randelli, 2020). In France, the work carried out as part of the LACCAVE project went in this direction and showed that the climate challenge needs to be met by innovations forming part of a strategic review at the winegrowing region or cluster level (Ollat *et al.*, 2022; Touzard and Hannin, 2023). This involves taking the following into account:

- changes in ecosystems, soils and climate, which can no longer be seen as unchanging conditions for wine quality
- opening up governance of winegrowing areas to other stakeholders involved in managing local resources
- experimentation with innovations in a wide range of interrelated fields (planting material, agricultural and oenological practices, ecosystem and risk management, certification and communication, etc.)
- combining these levers of action in adaptive strategies, anticipating potential paths and forks in the road, etc.

These new strategic directions, which are taking root in wine-producing regions, are in line with research developments that study the territorial dynamics of innovation in economics and management sciences. This work replaces the concept of the cluster, which is centred on local partnerships between companies in the same industry, with that of the "local innovation ecosystem" (Torre and Zimmermann, 2015; Suominen *et al.*, 2019), which aims to make better use of new conditions for innovation, bringing into play:

- partnerships with companies that are geographically close to each other but operate in different industries, such as for the provision of shared services or training, management support or innovation
- the co-creation of projects and shared values across a geographical area, for its promotion and the enhancing of its appeal, among other reasons
- more open interactions with the public
- the consideration of circular relationships with the surrounding environment and its natural resources, the sustainability of which must be ensured

An innovation ecosystem is a place where tacit, empirical and scientific knowledge can be exchanged between companies, local stakeholders, and universities and research bodies. It creates a favourable environment for the management of new territorial knowledge (Boyer *et al.*, 2021).

Work conducted in winegrowing regions has led to the framework for analysing innovation ecosystems being brought into action (Levy and Lubell, 2018; Marques *et al.*, 2021) or even to expand it by putting forward the concept of climate change adaptation strategies (Boyer and Touzard, 2021). What can be done to ensure networks, organizations and operational knowledge about climate change, its impacts and solutions are created in a more open and participative way? What factors can encourage cooperation between economic, political, scientific and civil society stakeholders for the development of these adaptation ecosystems in winegrowing regions? The work conducted as part of the LACCAVE project, in particular through James Boyer's doctoral thesis (2016a), has led to progress being made on these issues by interlinking several angles of analysis in three winegrowing regions.

A mixed method for studying regional innovation systems in French winegrowing areas

In order to study the role of innovation systems in the adaptation of French vineyards, we have chosen three contrasting winegrowing regions in which we have successively implemented three complementary approaches at the level of institutions, winegrowers and researchers.

The choice of three winegrowing regions and five areas of adaptation

Three winegrowing regions were selected on the basis of the importance of wine production in terms of value, the existence of R&D activities in viticulture and wine, and the fact that they belong to different climate zones: Aquitaine (oceanic), Languedoc-Roussillon (Mediterranean), and Champagne (continental). The effects of climate change observed and expected in these three regions differ slightly (Ollat *et al.*, 2022). The vineyards of Languedoc-Roussillon are already suffering from severe water stress, resulting in high alcohol concentrations and a drop in acidity. In contrast, Aquitaine has benefited from the rise in temperatures, though there are worrying effects on disease pressure and the characteristics of wines made from existing grape varieties (Merlot in particular). As for Champagne, which will probably be spared to a greater extent in the short term, it could also be prone to summer heatwaves, leading to greater disease pressure.

In addition, five areas were identified for adaptation to climate change, both as areas of action or innovation for winegrowers and as areas of research or experimentation for researchers: planting material, vineyard management methods (vine architecture, crop management sequences, soil and water management, etc.), parasite control measures, winemaking practices counteracting the effects of climate change, and spatial and economic strategies in a single terroir and further afield.

The competitiveness and the institutions of winegrowing regions

The first angle of analysis is the regional administrative level and considers both the economic competitiveness of each region's vineyards and the institutions with a role to play in climate change innovation and adaptation. The competitiveness of each winegrowing region was studied over the 2000–2014 period, based on the following indicators: their share of French wine production by value, their average productivity by value per hectare, and the average value of wine per hectolitre.[34] Institutions with an involvement in winegrowing regions are described according to their research, educational, advisory, testing or funding activities, in line with the resources (full-time equivalent employees, budget) devoted to R&D in viticulture or wine and a bibliometric analysis of viticulture and wine publications (2008–2014) by researchers and engineers using Web of Science databases[35] (Boyer and Touzard, 2016).

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[34] Data from the French Department of Agriculture and FranceAgriMer.

[35] The WoS, managed by the Institute for Scientific Information, which has an inventory of more than 10,000 journals. The keywords used link areas of adaptation to climate change, institutions, and the location of the authors.

Winegrower surveys

The second angle of analysis looks at winegrowers for each region and the actions they are taking to adapt to climate change. This study, presented in chapter II-1, was based on surveys of 87 winegrowers (28 in Champagne, 29 in Bordeaux and 30 in Languedoc) who make and sell PDO wines from their grapes. The sample was selected according to the criteria of relative economic size (two categories of companies in each region) and traditional or organic grape production, while ensuring an even spread of winegrowers in each region. The questionnaire covered the general characteristics of producers and their businesses, their perceptions of climate change and its effects, the actions undertaken in each of the adaptation areas, and requests for advice made or envisaged in each area. The aim was to place each winegrower's egocentric advisory networks into six categories of stakeholders belonging to the R&D institutions detailed in the previous study (Boyer and Touzard, 2021).

Wine R&D stakeholder surveys

The third angle of analysis directly concerns the actions of people working in viticulture and wine research and testing organizations (INRAE, CNRS, universities, the IFV, chambers of agriculture, wine trade associations, etc.). This third study was conducted in 2015 based on 94 interviews (41 in Languedoc-Roussillon, 34 in Bordeaux and 19 in Champagne). The sample was drawn from lists of researchers and engineers working in viticulture and wine, divided between 62 researchers and 32 engineers. The questionnaire takes into account information on the career and activity of each stakeholder, the importance of climate change in their work, the work they have produced and their projects in each adaptation area, and the ways in which their information communicated to winegrowers (personal ties, joint projects, talks, articles in technical journals, etc.) (Boyer 2016b).

Analysis and comparison of data from the three studies

A mixed method was used for the three studies (Labarthe and Schnebelin, 2023) and combined a qualitative analysis of the replies provided by the respondents and statistical analyses that sought to assess the influence of different factors (organizational, relational, career paths, etc.) on the commitment to adaptation action at winegrowing-area level (for winegrowers) or to knowledge creation in R&D (for researchers and engineers). The choice of variables to be explained (climate change perception, actions taken), explanatory variables and econometric models (multiple regression or logistic function) that link them together were presented in more technical articles (Boyer 2016b; Boyer and Touzard, 2021).

Results of the three studies on regional innovation systems and vineyard adaptation

Here we present the results of the three studies carried out on innovation systems in the selected winegrowing regions, highlighting the institutional and organizational conditions that impact their competitiveness and adaptation to climate change. These results will be compared and discussed in the conclusion to this chapter.

The competitiveness of winegrowing regions: a factor dependent on R&D intensity and wine trade association involvement

The first study showed that the competitiveness of winegrowing regions between 2000 and 2016 varied and was linked to the characteristics of their R&D institutions. Languedoc-Roussillon, which stands apart for its large surface area and production volume, and for the lower value of its wine (around €150/hL in 2016), saw its share of the value of French wine production fall at first and then rise from 2007, reaching 15% in 2016. In contrast, Champagne has the highest value per hectolitre (€1,100) from a smaller surface area (31,000 ha), making it by far the leading French winegrowing area in terms of value (more than €3 billion in production). Champagne's share of the value of French wine production rose sharply between 2000 and 2007 (from 22% to nearly 30%) and has remained stable since then. It is the most competitive winegrowing region according to our criteria. Bordeaux, the second largest winegrowing region in France in terms of surface area, volume and value, stands in between with regard to value per hectolitre (€400), and saw a sharp fall in share of production until 2008 (from 20% to 15%), since when it has risen to around 18%.

Analysis of the institutions that have a role to play in vineyard innovation shows the same general organization, with the presence in all regions of public research centres (INRAE or CNRS) and centres of education specializing in the industry (universities, engineering and business schools, and agricultural colleges), experimentation and consultancy organizations (IFV hubs, chambers of agriculture, etc.), wine trade associations and product protection and management bodies[36], government departments (DRAAF – regional directorates for food, agriculture and forestry, DDT – departmental directorates for the territories, FranceAgriMer), local authorities involved in viticulture and wine, and wine-related media organizations (specialist press, trade fairs, events). However, this infrastructure differs from one region to another, with organizations having varying levels of influence and being structured in different ways. The regions of Languedoc-Roussillon and Aquitaine are where France's main viticulture and wine R&D and training centres are located, accounting for more than two thirds of national budgets and full-time equivalent (FTE) employees, and nearly 60% of literature publications. Both regions are less competitive than Champagne, however. Does the stature of the institutions of a regional wine cluster not play a decisive role in France's competitiveness? The following two factors both disprove and back up this assertion:

- First, we need to take into account R&D intensity, which divides regional organization indicators (FTE, budget, publications, etc.) by the surface area or volume of each winegrowing area. Champagne stands in first place, with more than four R&D FTEs per 1,000 ha of vines in 2015, as opposed to 2.2 for Aquitaine and just 1.4 for Languedoc (Boyer and Touzard, 2016).
- Furthermore, the involvement of wine trade associations in R&D and innovation also appears to be a key factor. In Champagne, for example, the Comité Interprofessionnel du vin de Champagne (CIVC – a regional association of growers, cooperatives and merchants) spent more than €150 per hectare on R&D, compared to €12 by its Bordeaux counterpart, the CIVB, and just €2 by Languedoc-Roussillon's wine trade associations as a whole.

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[36] Known as *organismes de défense et de gestion*, or ODGs, in France

Winegrowers and their relationship with the regional innovation system: a key to their commitment to adaptation

Surveys of winegrowers in the three regions showed that they shared the same perceptions of climate change (see chapter II-1) and that most of them – 67% in Languedoc, 57% in Champagne and 52% in Bordeaux – had taken action as early as 2015 in an effort to deal with it. To adapt, winegrowers are using or planning to use the networks they have with stakeholders in the regional innovation system. These advisory relationships differ from one region to another. In Languedoc, winegrowers prefer to talk to colleagues or chambers of agriculture, whereas in Bordeaux, winegrowers tend to seek out advice from suppliers and research centres such as the Institute of Vine and Wine Science (ISVV). In Champagne, meanwhile, winegrowers say they mainly consult their wine trade association (CIVC). The three regions do have the following points in common, however (Boyer and Touzard, 2021):

- The financial situation of winegrowers has no influence on either their perception of climate change or the adaptation measures implemented.
- Winegrowers who routinely seek advice from chambers of agriculture, hire trainees and take part in industry events are more inclined to innovate to adapt than others.
- The level of education of winegrowers and their experience in the wine business have a positive influence on their perception of climate change and the likelihood of them innovating to adapt.
- Organic and biodynamic winegrowers are more concerned about climate change and more inclined to innovate to adapt.

Winegrower surveys show that their commitment to adapting to climate change is closely linked to their relationships with the organizations in their regional innovation system (research, advice, training), and that this commitment is more pronounced when they have developed strong environmental strategies, which ties in with the conclusions of research conducted in California (Levy and Lubell, 2018).

R&D stakeholders and their differing contributions to vineyard adaptation

Surveys of staff at research, training and development organizations provide fresh information on their involvement in the adaptation of winegrowers in each region. Regional variations were noted. The issue of climate change as a whole is more important for those in Languedoc-Roussillon and Bordeaux than in Champagne, and in terms of areas of adaptation, Languedoc, for example, focuses more on water management and Bordeaux on oenology. Nevertheless, there are points in common between the three regions here also:

- The level of academic excellence (publications and degrees) and personal details (age, gender, etc.) of R&D staff do not significantly affect their involvement in the production of climate change knowledge.
- The field of research or intervention is a key factor, however. R&D staff working on planting material or vineyard management are more invested in producing climate change knowledge than those working on disease control, oenology or spatial and economic strategies.
- Generally speaking, staff directly involved in research (INRAE, universities and, to a lesser extent, the IFV) tend to integrate the issue of climate change into their work more than engineers involved with consultancy, training or testing organizations.

- Conversely, the latter group interact more frequently with winegrowers, which points to a dichotomy of some kind: researchers are more concerned about climate change than engineers and advisers (chambers of agriculture, wine trade associations, oenologists, etc.) said they were in 2015, but have less contact with winegrowers than them.

Surveys of staff in the innovation system in each winegrowing area in the three regions revealed a gap between researchers promoting the climate issue and the staff of advisory and development organizations, for whom this issue was less of a factor in their work. However, the climate issue was already a major concern for winegrowers, a majority of whom said they were taking action to deal with it (see chapter II-1). The findings point to a knowledge gap in the innovation system in the three regions in 2015, because of the reluctance of some intermediary stakeholders to take the climate issue on board. These results underlined the importance of developing interdisciplinary and participatory research projects to encourage more direct interaction on climate issues between winegrowers and researchers in each region.

Conclusion

Studies carried out between 2014 and 2016 in the winegrowing regions of Languedoc, Champagne and Bordeaux revealed the following:

- The competitiveness of winegrowing regions was clearly linked to the intensity of their R&D activities and the involvement of regional wine trade associations.
- The majority of winegrowers were concerned by climate issues and were taking steps to deal with them, particularly those who had forged strong ties with the regional innovation system and pursued agroecological practices.
- However, the level of involvement of the stakeholders in this innovation system differed when it came to the production of knowledge for climate change adaptation, with researchers more involved than intermediaries from winegrowing organizations.

From 2016 onwards, these results supported a new direction for the LACCAVE project, as research began to involve winegrowing organizations from each winegrowing region more and directly promoting interaction between researchers and winegrowers (Ollat *et al.*, 2016b). This prompted the organization of foresight workshops in seven winegrowing regions (chapter II-7), not to mention local initiatives undertaken by researchers (chapters II-5 and II-6), and, increasingly, by staff from chambers of agriculture, wine trade associations, the IFV or appellation associations and cooperative wineries (box II-3-1). The observations made since 2016 on the development of projects and relationships in French wine clusters suggest that climate change has become a central issue, one linked with that of the environment, with "local ecosystems for adapting to climate change" being built (Boyer and Touzard, 2021; Touzard and Hannin, 2023). Uncertain in nature, this development may depend on a number of conditions:

- The positive effect of R&D intensity on the competitiveness of winegrowing areas, shown for the period 2000–2014, is likely also valid for innovations contributing to climate change adaptation, subject to heightened appreciation of this issue across all R&D organizations, which seems to be the case today.

Box II-3-1. 2030 Val de Loire industry plan

Founded in 2019, the Val de Loire Professional Council is a forum for the industry's elected representatives (2,700 winegrowers and 410 merchants) and its partners (chambers of agriculture, the IFV, nursery owners, training centres, the Mutualité Sociale Agricole (MSA – a body that protects the rights of agricultural workers), the INAO, etc.). In association with a local technical council, it has drawn up the 2030 Val de Loire industry plan, a large section of which is devoted to climate change adaptation. The plan sets targets for results and resources up to 2030, and is re-assessed every year with the aid of around a hundred monitoring indicators. The aim of this group strategy is to help winegrowing in the Loire Valley and its districts adapt more quickly to climate change.

Two major priority objectives have been identified:

1. **To improve knowledge of winegrowing terroirs on a field-by-field basis by 2030, using mapping** to adapt wine production, develop practices and relocate specific fields:
   - characterization of terroirs (1:10,000) and daily water balance at field level (WaLIS model), with 57,600 ha mapped by 2022 (87% of vineyards)
   - mapping of frost-protection equipment
   - atlas of climate and agroclimate indicators for the near and distant future (2050 and 2100) and at local level in 2022 (100% of vineyards)
   - climate zoning at field level for interested PDOs, from 2023
   - meteorological monitoring platform as part of the National Vineyard Dieback Plan (PNDV), from 2023
2. **To promote grapevines adapted** to climate change:
   - strengthen selection and varietal creation, through rootstocks, grape varieties and clones
   - introduce "varieties of interest for adaptation"
   - conserve and explore existing diversity through heritage grape varieties and non-Loire Valley grape varieties and through exploration and conservation programmes for our iconic grape varieties in France and abroad (Chenin, Sauvignon, etc.)

Two pillars have been strengthened, as they are crucial to the success of the industry's adaptation:

1. **Development of research and testing.** Coordination and prioritization of projects at the Val de Loire Technical Council, projects trialling innovative management systems and building on expertise (Root Loire Valley, CLIMENVI, 4, SICTAG, REDCLIM, among others*);
2. **Promotion of the transfer of technical informatio**n, both digitally through a group-based open-access platform (techniloire.com) and with the creation of a calendar of events for winegrowers, technicians and elected representatives in the industry (foresight sessions, conferences, feedback from R&D projects, training for technicians and winegrowers, demonstrations, discussion groups, etc.).

* Root Loire Valley: Quels porte-greffes face aux enjeux actuels et à venir de la viticulture dans le Val de Loire ? [Which rootstocks are needed to meet current and future challenges facing winegrowing in the Loire Valley?]; CLIMENVI (see box II-5-4); ADACLIM: Adaptations viticoles et œnologiques aux conséquences du changement climatique en Val de Loire [Adapting viticulture and oenology to the effects of climate change in the Loire Valley]; SICTAG: Système innovant d'aide à la décision connecté et de gestion efficiente en temps réel des tours anti-gel du Val de Loire [Smart, innovative decision support system for efficient real-time management of frost-protection turbines in the Loire Valley]; REDCLIM: Réduction de produits phytosanitaires et changement climatique en Val de Loire [Reducing the use of plant protection products and climate change in the Loire Valley].

- The role a regional wine trade association can play in the adoption of innovations (such as the CIVC in Champagne or InterLoire in the Loire Valley, see box II-3-1) can be seen as a favourable condition for adaptation in winegrowing areas. These associations, which are run by the wine-producing companies, are very well placed to define research needs, co-fund them, and build partnerships and knowledge networks.
- However, the rising pace of climate change means innovation systems in each winegrowing area must be more responsive and flexible, and direct links between stakeholders have to be improved, not least between researchers and winegrowers. Research and teaching projects are a prerequisite for adaptation, as are events and spaces that promote participation at different levels in winegrowing regions and between them. This aspect is highlighted by research into "local innovation ecosystems" (Suominem *et al.*, 2019).
- In addition to participation, opening up innovation systems to other industries, local authorities and civil society can help create the necessary conditions for adaptation. This means sharing knowledge more effectively with wine consumers, but also with those involved in the management of local resources (land, water, etc.), and even exploring more radical solutions, including diversifying production, which could involve viticulture Climathons at local level (chapter II-5). In this regard, the innovation systems of winegrowing regions, which until now have involved an industry-based approach, could become part of a "local ecosystem for adapting to climate change", run jointly with local authorities responsible for local climate-air-energy plans (PCAETs) and associated community councils.
- Lastly, with the climate challenge giving rise to differing approaches to adaptation, from "highly technological" to "highly agroecological" options (Schnebelin *et al.*, 2022), the development of adaptive, joint management of local resources would appear to be vitally important. The aim is to take a fresh look at terroirs, which have been greatly affected by climate change, and the way they are managed, by introducing carbon mitigation and capture actions. These are areas where genuine opportunities are open to winegrowers (management of logistics, soils, landscapes, etc.). Research into local innovation ecosystems has also highlighted this dimension and promoted a circular or even "metabolic" vision of development.

Across the board, the ability of stakeholders in winegrowing areas to build local ecosystems that take the form of more open collaboration networks between businesses, teaching and research organizations, professional organizations, local authorities, civil society, etc. appears to be the main condition for adapting winegrowing areas to climate change.

CHAPTER 4

DEVELOPING KNOWLEDGE FOR TRAINING

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Introduction

The creation of new capabilities for addressing climate change on training courses, particularly those focusing on the viticulture and wine industry, is just one of many well-known attributes of the LACCAVE project, along with its ability to produce research results, bring teams together, help create networks, and encourage forward-thinking strategic dialogue with the industry. This chapter looks at that contribution and the key role of education in the success of climate change strategies (Aigrain *et al.*, 2021). A number of research projects on this topic in recent years have all aimed to communicate results through vocational, continuing and entry-level training channels. Furthermore, students of viticulture and oenology are now aware that climate change will have a major impact on their future careers. Similarly, it is clear that no single discipline or specialist teacher can provide a solution to a challenge as complex as climate change. Only a systemic and interdisciplinary approach, of the kind that guided the LACCAVE project, can prevail in education. Finally, structural changes are taking place in education, with the development of teaching methods designed to make learners not so much receivers of knowledge as active participants; the increasing use of digital tools and distance-learning technologies based on the availability of large data sets (box II-4-1); and greater importance attached to "teaching innovations" (Lemaître, 2018). These developments have come in response to a certain fatigue with lectures and to a post-lockdown appetite for new approaches that are more group-based and fun. Agronomy schools in Montpellier, for example, have been running "burning issue" workshops, flipped learning classes, and annual "teaching innovation" days.

It is against this backdrop that this chapter presents a number of innovative and sometimes fun training courses and teaching aids, aimed at a variety of audiences and levels and which address the climate issues facing the viticulture and wine industry. The results and approaches developed by LACCAVE are used to illustrate this point: a training course for teaching staff at winemaking colleges; an innovative interactive mapping tool; a future-oriented, participatory role-play game; a survey entitled "Tomorrow's climate in my vineyards" and compiled by student engineers for winegrowers; and a serious game about the participative ecodesign of winegrowing techniques. These examples will allow us to learn lessons and highlight teaching tools and methods that can improve training and help us take action in new contexts shaped by climate change.

Box II-4-1. The importance of data and knowledge-sharing

If we are to meet the challenge of climate change, it is vital that winegrowers share their knowledge and work together to find sustainable solutions. Data collection and access are crucial to creating innovative solutions. For this to happen, however, data collection must be straightforward and the data well described, made available to large communities, neither complex nor redundant, and applicable to the production of new knowledge.

More and more data are now available thanks to the use of digital technologies throughout the wine production chain – including smartphones, sensors, drones, smart equipment, satellites, social media – as well as the widespread use of computerized services (traceability, technical and financial decision support systems, electronic declarations, etc.). How can this data be leveraged and processed to allow industry stakeholders and consumers to make best use of it? By combining big data with appropriate analysis and modelling methods (artificial intelligence, predictive models, etc.), we can produce new knowledge, make correct decisions and diagnose problems. If we are to develop this potential to the full, we must structure and link the data.

The use of a wide range of data for understanding the impacts of climate change and supporting adaptation decisions means that these data must be FAIR (based on the principles of findability, accessibility, interoperability, and reusability), their origin known, and their quality specified. Standardized metadata must clearly describe the data so that they can be understood (What? Where? How? When?), managed (electronically and administratively) and linked. To ensure that different data complement and build on each other, we need to make sure that we are "talking" about the same thing. Understanding can be improved by sharing controlled vocabularies (ontologies) with semantics defined by a clear, precise and concise description. For example, observation data from various sites can be linked to different phenological scales. If we have information characterizing the data (metadata), we can then reconcile it all, compare it and use it together.

Setting up a training programme for teachers at viticulture colleges

Recent climate change and the impact it is already having on the viticulture and wine industry are forcing training organizations to address the issue and adapt their teaching programmes accordingly. The Joint Research Unit for Ecophysiology and Functional Genomics of Grapevine (EGFV) developed a training course for teachers at viticulture colleges. The idea was to share climate change knowledge acquired through the LACCAVE project and levers for adaptation and mitigation in the viticulture and wine industry. The course also offers support for the co-creation of teaching content for new training programmes. An interdisciplinary team of trainers involved in the LACCAVE project worked on the course, with industry professionals also contributing. It took place over two non-consecutive days so teams could work together. The course comprised four sessions.

Session 1: general knowledge of climate change at a global level

This session took the form of conventional lessons that included video clips and exercises and providing learners with general knowledge about the climate and modelling, the greenhouse effect and recent climate change. Application exercises dealt with such topics as climate indicators and the availability of weather data.

Session 2: climate change in the viticulture and wine industry

The first module outlined the consequences of climate change on vine development and wine quality (phenological advance, grape and wine composition, yield and quality). The perception of climate change by industry stakeholders was then examined from two angles: that of winegrowers, based on a worldwide survey (see chapter II-1); and of oenologists and consumers in response to changes in the aromatic profile of wine (see chapters I-4 and II-2).

Session 3: adaptation to climate change

Adaptation was covered in a workshop that included cross-functional feedback. Learners were divided into smaller groups made up of teaching teams from different colleges. Four adaptation topics were selected:

- responses to climate hazards
- adaptation through planting matter
- adaptation through agricultural practices
- adaptation through oenological practices

Each group was asked to work on its chosen topic and create a training module, which it then presented it to the class. This was followed by a discussion. The groups each had to specify learning objectives for their modules and a detailed programme setting out the teaching methods (lectures, practical work, tutorials, field experiments, etc.). Two experts in the field were on hand to support the groups and share their thoughts and ideas.

As well as learning about adaptation, college teachers were able to use the module to co-create future teaching programmes on these topics and to exchange ideas with their colleagues. Day two involved cross-functional feedback, with tutors monitoring the groups providing additional information.

Session 4: regulatory responses to climate change

A presentation by the French National Institute of Quality and Origin (INAO) addressed the link between adaptation and regulatory change in France.

Session 5: climate change mitigation

Actions designed to reduce the greenhouse gases emitted by vineyards were addressed in three complementary presentations, which were followed by discussions:

- the results of "carbon audits" carried out by the Bordeaux Wine Trade Association, and actions taken to limit the industry's carbon footprint
- the results of the LIFE-ADVICLIM research project, which assesses greenhouse gases emitted due to winegrowing practices at field level
- feedback from a wine estate firmly committed to reducing its carbon footprint

The course ended with learners evaluating the teaching content and the way the module had been run. This evaluation will allow us to tailor training courses to the expectations of teachers at viticulture colleges in terms of climate change and adaptation, and enhance existing teaching resources.

An interactive mapping tool for studying terroirs in the context of climate change

There is more to promoting a research project than scientific reports and academic knowledge. Accessible information channels need to be created to engage with the public.

Opening up research to the viticulture and wine industry

With this in mind, a story map[37] was created to communicate the results of the LIFE-ADVICLIM project to viticulture and wine industry stakeholders. This resource also has great educational potential: it provides a terroir-based illustration of the classes taught at viticulture colleges.

An easy-to-use platform

The development of platforms in recent years has led to the emergence of significantly more story mapping tools (Caquard and Dimitrovas, 2017). We chose to use the Esri web app[38] because maps produced with this tool were easy to use and were "conversant" with the graphic elements created to visualize the project findings.

The various strands of this research (study site, local climates, climate modelling, current and future vine phenology, adaptation and mitigation of greenhouse gases) form the narrative thread. The results were summarized and made more accessible in some cases to adapt them to different audiences, and ranged from the simplest of hooks to more complex results presented in scientific articles. The maps are interactive, with readers free to question the data they contain. Photos, videos, hyperlinks and commentaries are also included to enhance storytelling.

Reveal to industry professionals and students

The mapping tool was presented to industry professionals at a LIFE-ADVICLIM project seminar in Bordeaux in 2019. They gave feedback at the end of the day and some of the more complex aspects of elements presented were discussed. The mapping tool was the subject of an article published in *IVES Technical Reviews Vine and Wine* (David *et al.*, 2023). The article and its English translation have had thousands of views.

The story map was presented as an educational tool at the training course for teachers at viticulture colleges (see above), who were shown how it could be used to support the hands-on work they do with their students and help them understand climate change in the viticulture and wine industry.

It is also used by students at Bordeaux Sciences Agro (as part of the viticulture-oenology option) as a climate change information resource.

Ultimately, the tool could provide the basis for the development of a specific teaching aid for the subject.

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[37] https://www-iuem.univ-brest.fr/wapps/letg/adviclim/BDX/EN/#.

[38] https://www.esri.com.

A foresight-based, participatory role-playing game for raising awareness of the need to adapt to climate change

L'Institut Agro Montpellier has specialized in viticulture and wine for 150 years and offers seven course programmes on the subject of viticulture for 280 students. A new climate change learning module was introduced in 2019 for 30 student engineers taking the viticulture-oenology option. The module takes an interdisciplinary approach and gives students an insight into the complexity of the relationships between stakeholders and the possible role of participatory reflection based on foresight scenarios. The module draws directly on work conducted as part of the LACCAVE project, namely local participatory events (chapter II-5) and the national foresight strategy (chapter II-7) (Aigrain *et al.*, 2016a; Aigrain *et al.*, 2016c).

The aim is to put students in situations that will raise their awareness of the issues, impacts and risks that climate change poses to the industry, and of the benefits of foresight-based and participatory approaches as tools for developing adaptation strategies. There is also the need for them to understand the role of innovation in an industry that demands it in order to meet the major challenges of today but also shies away from it out of its sometimes excessive belief in "tradition".

In this case, interdisciplinarity is backed up by a foresight-based approach designed to represent the system, envisage potential futures, empower stakeholders and help bring about strategic decisions and specific actions. The method was used in the LACCAVE project to develop climate change scenarios with the aid of more than 450 industry professionals (chapter II-7; Aigrain *et al.*, 2016b). A short, two-hour introduction to the principles of foresight studies is recommended, followed by four half-day sessions.

Session 1: acquiring knowledge

The teacher starts by presenting the challenges that climate change poses to the industry and the impacts and levers for adaptation and mitigation. The students then identify avenues for further scientific study and form groups to look at each of them. In their groups, they prepare a presentation based on documents uploaded to the learning platform and their notes from previous classes. The students then present these essential insights to the (flipped) class so that they can share their thoughts.

Session 2: understanding the relationships between stakeholders and the need for consultation through role-playing

Students are divided into groups, each of which has to take on the role of an industry stakeholder called upon to implement adaptation measures (e.g. "You are an organic winegrower in the Languedoc PDO, a PDO union, etc."). Each group has an information sheet setting out its situation, objectives, constraints, any plans it may have and its relationships with other stakeholders, regardless of whether or they are involved in the role play or not. The session is divided into four parts:

- **Part 1:** Each group must comprehend the stakeholder's activity and consider ways of adapting it. Some of the obstacles identified require subsequent dialogue with another stakeholder (represented by another group).

- **Part 2:** Each group is split into two teams. One team puts a series of prepared questions to one of the two stakeholder groups. The other team answers questions from another visiting team.
- **Part 3:** The groups reconvene and prepare a summary of the meetings, their progress and any remaining obstacles. They then create four slides outlining the specific issues facing their stakeholder, the objectives identified, the levers for action and obstacles encountered, and the results of meetings with other stakeholders.
- **Part 4:** The groups use the slides to present their work and conclusions. General conclusions are then drawn in a discussion with the other students and teachers.

In the final hour, the professor explains how the national strategy is structured, in line with the foresight study conducted at LACCAVE[39] and presented to the French Minister of Agriculture in August 2021 (chapter II-7; Hannin *et al.*, 2021).

Session 3: analyse an actual vineyard situation

Making the most of meetings already scheduled with a winegrower (or setting up new meetings), students analyse the issue of climate change in a winegrowing business with a view to presenting a diagnosis and making recommendations for adaptation and mitigation. These real-life cases lead on to class presentations, debates between students and discussions with teachers.

Session 4: organizing an industry event

The students organize a conference and invite other students, their teachers and industry stakeholders, some of whom (around six) are invited to take part in a round-table discussion. The students present a summary of the issues and the status of national and international adaptation and mitigation strategies for the viticulture and wine industry. The groups take turns to present the updated results of the session 2 role plays. The presentations elicit reactions from the round table, which is led by two of the students. To inject some fun into proceedings, the round table can take on the guise of a jury and award a prize to the most convincing person in their role.

Student feedback is then gathered in a final role play. Ideally involving all the teachers on the course, this session provides an opportunity to reflect as a class on more effective integration of the climate change issue into the teaching programme.

Agroclimatic foresight model produced by engineering students for a winegrowing region

In terms of adapting industries to climate change, the needs of agriculture advisory bodies may be addressed by what engineering students learn in their courses. This is what the “Tomorrow’s climate in my vineyards” initiative, in which a group of engineering

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[39] Through the foresight work package headed up from 2013 by INRA (now INRAE), Montpellier SupAgro, FranceAgriMer and the INAO.

students conduct an audit of vineyards every year, aims to show. Created in 2021 as part of a partnership between some French chambers of agriculture and the engineering school UniLaSalle Rouen, the initiative:

- puts engineering students face to face with real situations in the wine industry
- creates deliverables that agriculture advisory bodies can use
- integrates this work into broader viticulture adaptation actions undertaken by agriculture bodies such as chambers of agriculture

How the initiative works

Around 20 winegrowers are approached each year by their partner chamber of agriculture and asked if they are interested in taking part in the initiative. Each winegrower is then interviewed for an hour by two students and provides input for the various components of the audit. The student pairs then spend the next week analysing their respective vineyard, with all of them following the same approach. Finally, the deliverables are formatted, checked by supervisors and submitted to the partner agriculture development body.

Analysis of winegrower perceptions of past developments

The first part of the audit focuses on how winegrowers feel about climate change and the impact it has already had on their vineyards. Given that these are subjective opinions, there may be some bias in relation to actual trends. The analysis conducted by the engineering students involves, for each question asked, the following:

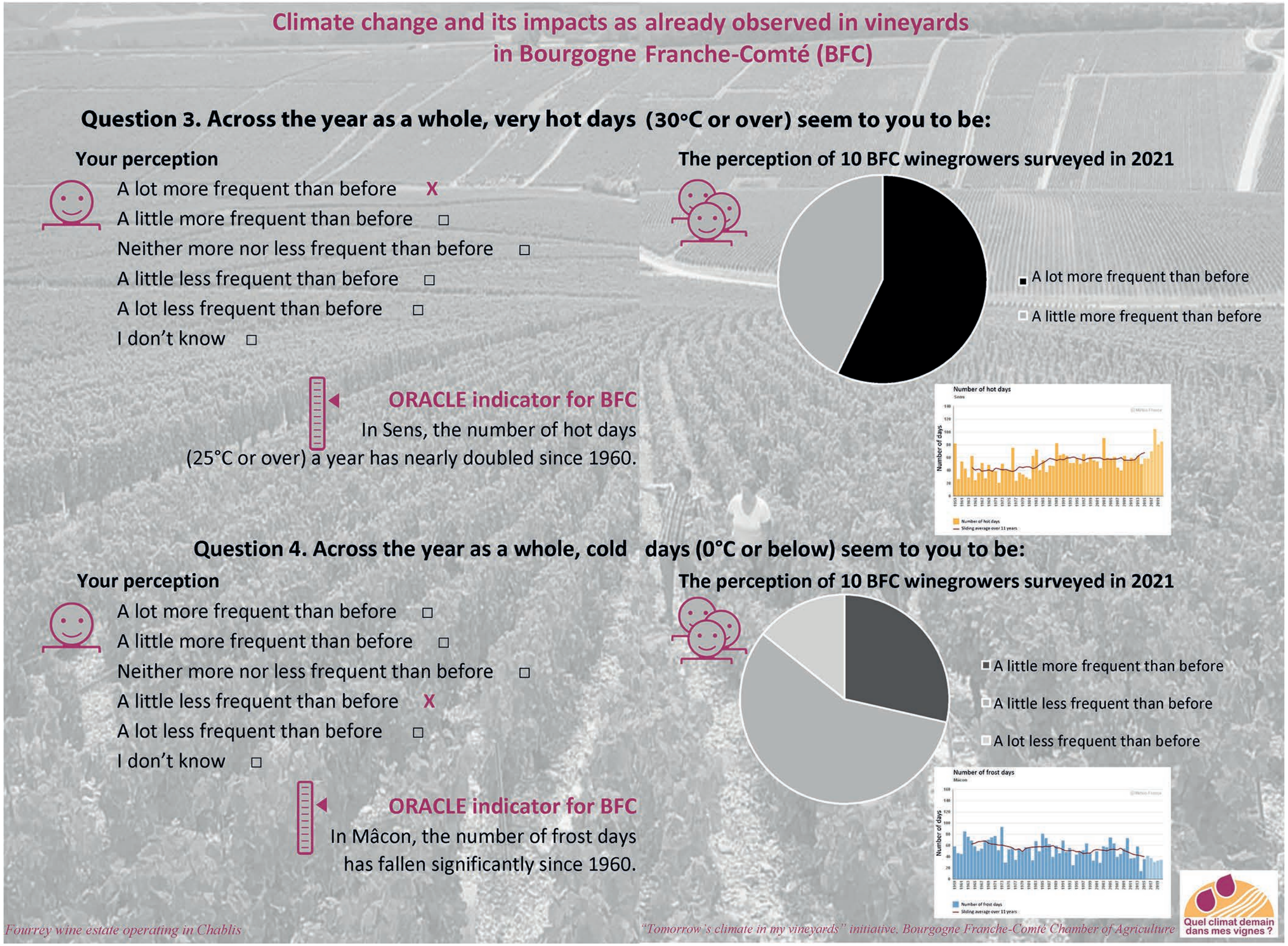
- compiling statistics on the responses of all winegrowers surveyed to identify any possible collective bias in their views
- ascertaining whether the Regional Observatory on Agriculture and Climate Change (ORACLE) covering the survey area has an indicator providing an objective response and then explaining this

Winegrower opinion survey on the national strategy for the viticulture and wine industry

The second part of the audit concerns winegrower opinions on the levers for adapting to climate change detailed in the "National viticulture and wine industry strategy to deal with climate change", approved in 2021 by INAO, FranceAgriMer, INRAE and the IFV (chapter II-7). These opinions are expressed with a degree of support or opposition. The analysis carried out by the engineering students involves, first of all and for each question asked, compiling statistics on the answers of all the winegrowers surveyed, and then ranking collective support for the various adaptation levers proposed in the area being studied.

Climate projections on the impact of viticulture and adaptation on a local scale

Part three of the audit looks at the future impact of climate change and the ways in which winegrowing businesses can adapt to it. Each winegrower chooses five key adaptation issues from a list of 15. The engineering students analyse future developments in agro-climatic indicators relating to these issues, using climate projections from the DRIAS Futures of Climate portal for the SAFRAN grid point closest to the winegrowing business being studied. The calculations are made in Excel, using files from the ClimA-XXI tool,



Climate change and its impacts as already observed in vineyards in Bourgogne Franche-Comté (BFC)

Question 3. Across the year as a whole, very hot days (30°C or over) seem to you to be:

Your perception

- A lot more frequent than before X
- A little more frequent than before ☐
- Neither more nor less frequent than before ☐
- A little less frequent than before ☐
- A lot less frequent than before ☐
- I don't know ☐

The perception of 10 BFC winegrowers surveyed in 2021

■ A lot more frequent than before

☐ A little more frequent than before

ORACLE indicator for BFC

In Sens, the number of hot days (25°C or over) a year has nearly doubled since 1960.

Question 4. Across the year as a whole, cold days (0°C or below) seem to you to be:

Your perception

- A lot more frequent than before ☐
- A little more frequent than before ☐
- Neither more nor less frequent than before ☐
- A little less frequent than before X
- A lot less frequent than before ☐
- I don't know ☐

The perception of 10 BFC winegrowers surveyed in 2021

■ A little more frequent than before

☐ A little less frequent than before

☐ A lot less frequent than before

ORACLE indicator for BFC

In Mâcon, the number of frost days has fallen significantly since 1960.

Fourrey wine estate operating in Chablis

"Tomorrow's climate in my vineyards" initiative, Bourgogne Franche-Comté Chamber of Agriculture

Quel climat demain dans mes vignes ?

Figure II-4-1. Inside pages of the summary produced by the students focusing on how winegrowers feel about climate change and the impact it is already having on their vineyards.

which covers 70 administrative departments in mainland France (box II-4-2). Depending on the future development of these indicators, the engineering students propose ways of adapting them, based on previous studies.

Table II-4-1. Example of a summary produced by the students focusing on the future impacts and adaptation challenges for a given winegrowing business. Climate change: expected adaptations for my vineyard. ***Mathieu Cathala estate (Sainte-Valière)***

153 mm (avg.) (min: +5 mm; max: +278 mm)	**Water conditions during dormancy** (rain – PET from 01/11 to 15/03)	**136 mm (avg.)** (min: +44 mm; max: +336 mm)	**96 mm (avg.)** (min: −65 mm; max: +326 mm)	***86 mm (avg.)*** *(min: −92 mm; max: +348 mm)*
2 years out of 10	**Risk of frost during budburst** (year with at least one day of frost after Grenache budburst)	**0 years out of 10** No adaptation needed in short term	1 year out of 10	1 year out of 10
−456 mm (avg.) (min: −577 mm; max: −315 mm)	**Water conditions during dormancy** (rain –PET from 01/04 to 30/09)	**−532 mm (avg.)** (min: −793 mm; max: −252 mm) Adaptations: reduced planting density/goblet pruning/leaf area management/ irrigation/ more resistant planting matter/ natural or artificial shade	**−530 mm (avg.)** (min: −788 mm; max: −353 mm)	***−616 mm (avg.)*** *(min: −811 mm; max: −352 mm)*
26 days (avg.) (min: 9 days; max: 58 days)	**Number of very hot days in growing season** (TX ≥ 30°C from 01/04 to 30/09)	**37 days (avg.)** (min: 8 days; max: 78 days) Adaptations: natural or artificial shade/more resistant planting matter/north-facing slopes if possible	**44 days (avg.)** (min: 13 days; max: 72 days)	***62 days (avg.)*** *(min: 27 days; max: 76 days)*
19.4°C (avg.) (min: 17.3°C; max: 20.9°C)	**Temperature at night during berry maturation** (Grenache)	**21.1°C (avg.)** (min: 18.7°C; max: 23.8°C) Adaptations: early-morning harvest, harvest cooling equipment, later planting matter	**21.6°C (avg.)** (min: 17.7°C; max: 24.2°C)	***22.7°C (avg.)*** *(min: 20.1°C; max: 27.3°C)*
1991–2000		2021–2030	2041–2050	*2091–2100*

"Tomorrow's climate in my vineyards" initiative, Aude Chamber of Agriculture
RCP 4.5 scenario/Aladin 6.3 model/PG 3505/ ClimA-XXI calculation/DRIAS 2020 data

Presentation

The study concludes with an oral presentation given by the engineering students to the business partners (winegrowers and advisers). Each winegrower is given three deliverables dealing with their specific case. The partner body is free to consider rolling them out to more winegrowers.

New skills for engineering students

This exercise provides engineering students with a body of skills relating to climate change adaptation engineering in an agricultural sector:

- the ability to draw on previously acquired fundamentals, such as the choice of RCP scenarios, future climate descriptions, impacts on phenology and vine growth, and levers for adaptation
- command of the technical environment of agroclimatic projections, using the DRIAS portal and calculating and interpreting agroclimatic indicators
- the ability to share results with stakeholders in the field in a usable format

Motivating factors for the partner agriculture body

For organizations already involved in adaptation, the initiative provides clarity on the following:

- the possibility of winegrowers receiving broadly available information and advice
- promotion of the key aspects of the "National viticulture and wine industry strategy to deal with climate change" on a local level and the interactions that will take place with the national flagbearers of the strategy
- the need among winegrowers for individual support

Points to watch and future outlook

There are two points teaching staff must watch out for:

- While some aspects are binding (e.g. the format of the deliverables), students must be given the freedom to take initiative and reflect (e.g. in creating files for calculating agroclimatic indicators).
- Prior to the deliverables being sent out to winegrowers, teaching staff should check the documents produced by the students thoroughly to ensure they are of good quality.

In terms of future outlook and assuming it is rolled out in a sufficiently large area, it should be noted that the "Tomorrow's climate in my vineyards" initiative could provide feedback from the field for the National viticulture and wine industry strategy to deal with climate change.

Vitigame, a serious game that raises awareness of levers for reducing environmental impacts

The Angers School of Agriculture (École supérieure des agricultures – ESA) trains 250 students a year in the wine industry: distance-learning diploma, professional degree, international master's degree, agricultural engineer degree with major in "vine and wine".

Box II-4-2. ClimA-XXI, a tool for anticipating agriculture's adaptation to climate change at local level

General details

Full name: Climat et Agriculture au XXI^{e} siècle

Objective: to provide a local assessment of the feasibility of agricultural production in the twenty-first century

Descriptors analysed: climate and agroclimate indicators

Climate service used: DRIAS Futures of Climate portal

RCP scenarios used: 2.6/4.5/8.5

Timelines analysed: 1976–2005, 2021–2050 and 2071–2100 (any 30-year period may be used)

Climate model used: ALADIN 6.3 (any EURO-CORDEX model may be used)

Mapping method: analysis using SAFRAN grid point

Geographical area: mainland France (overseas territories may be used)

Year created: 2015, with updates in 2017 and 2020

Software program: Excel

Number of users: around 150 on 1 March 2023

Access to the tool

Training: compulsory (two-day fee-paying course given by Resolia)

User licence: free

Organizations involved: chambers of agriculture, other training and agriculture advisory bodies

Use of the tool

Format: one Excel file for each case studied (SAFRAN grid point/agroclimate indicator/RCP scenario) and grouping of files by case (by client, assignment, etc.)

Examples of analyses: farm audits, industry strategies, regional vulnerabilities

Types of value creation: awareness-raising/information, continuous learning, initial training, agriculture advisory services

Management of user network

Notification of tool upgrades

Distribution of information sheets: ClimA-XXI instructions

Events: ClimA-XXI workshops

Tool upgrades

Roll-out of expert versions with more extensive calculation files and structuring by ClimA-XXI adaptation theme/viticulture: completed

Since 2010, the Food Products and Processes research unit (USC GRAPPE)[40] (ESA-INRAE) has been devoting its energies to the assessment of winegrowing practices through life cycle analysis (LCA), a comprehensive and globally recognized environmental assessment method that takes into account the impact of global warming and participatory viticulture ecodesign (Perrin *et al.*, 2022). The Eco3vic research project[41] and Anthony Rouault's doctoral thesis established a participatory viticulture ecodesign approach based on LCA (Rouault *et al.*, 2020). The prototype for a serious game created for winegrowing ecodesign workshops was trialled and proved its worth as an educational tool. This has now led to the creation of the Vitigame kit, which also includes Vit'LCA, an LCA viticulture calculator developed by the team. Their use in teaching, leading workshops, vineyard management and foresight studies is helping advisers, teachers, students and winegrowers to gain a grasp of the concept of participatory ecodesign.

A serious game promoting participatory viticulture ecodesign

Vitigame takes an innovative and motivational educational approach to raising awareness among viticulture stakeholders of the environmental impacts and mitigation levers involved in an annual crop management sequence, drawing them into the future technical or strategic decision-making process.

Based on real-life examples of integrated and organic winegrowing, Vitigame includes field fact sheets, the crop management sequence used and the LCA results, a playing board, cards for each operation and four-day weather reports including health risks, phenological stage, precipitation and forecasts. It also features three booklets setting out the rules of the game, the causes of environmental impacts and mitigation solutions, as well as active ingredients and plant protection products available, their impacts and key information on optimizing doses. Calculations can be made using Vit'LCA.

Vitigame is played by six to eight players, with each one taking on a different role. Games are overseen by a game master, someone familiar with viticulture and trained in LCA and Vitigame (figure II-4.2).

Figure II-4.2. The Vitigame serious game. © Anthony Congnard.

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[40] An agri-food research group that studies products and processes.

[41] Collective ecodesign as a means of supporting changes in viticulture practices.

The game involves three stages:

1. The game master presents the selected crop management sequence, its impacts and their causes, and the proposed impact mitigation strategies, with their technical levers. The group starts planning, chooses a strategy and soil management practices, and can buy additional mitigation levers.
2. The crop management sequence is ecodesigned, practice by practice, taking into account the information given in the weather reports. The game master ensures that vineyard interventions are performed on time, warns of any risks and, if necessary, imposes penalties in the form of "downy mildew or powdery mildew attacks". Different groups can work on the same case and compare the effectiveness of their selected strategies.
3. There are three opportunities for dialogue and reflection on the chosen management sequence based on: first, the choices made by the players and their effects (crop health, yield and quality) based on the expertise of the game master; second, each group presents its choices to the others, explaining the strategies chosen and discussing them; finally, the game master presents the results of the LCA of the ecodesigned management sequences, comparing them with the initial cases calculated using Vit'LCA software.

The second year of the Viticulture-Oenology diploma at the ESA and the third year of its agricultural engineering course include game sessions, which take place following awareness courses on the LCA and ecodesign in viticulture. Whatever the audience, Vitigame helps raise awareness of environmental issues and mitigation levers, and provides a unique learning opportunity for the creation of a comprehensive crop management sequence that takes multiple constraints into account. The results are significant, with students achieving an average reduction in impact of between 20% and 30%, an outcome not dissimilar to that of the winegrowers' workshops.

This growing awareness has led to a greater willingness to take the environmental dimension into account and make use of LCA and ecodesign in engineering students' final viticulture dissertations. Vitigame has been on sale since January 2023, with training courses available for teachers, companies and field advisers looking to use it (Renaud-Gentié *et al.*, 2022).

Outlook

The Vitarbae research project (2023–2026) aims to make use of serious games to create a comprehensive support programme for teaching and advising winegrowers and arboriculturists. In terms of viticulture, it will include Vitigame and a new game to be created on the establishment of vineyards and drawing on mitigation levers, an economic evaluation of changes in practices, the impact on biodiversity, and easier access to LCA results for decision-making. Finally, translating the game into English would allow it to be used on English-language training courses and distributed around the world.

Conclusion

The educational innovations presented in this chapter illustrate, with different objectives, audiences and angles, various ways of making the most of climate change research findings and meeting industry expectations in the face of this major challenge. It does not claim to present all recent initiatives, which are evolving all the time. Collaboration within teaching networks and their consolidation through research projects involving teacher-researchers can only boost the development of these initiatives and make them better.

It is quite remarkable that all these innovations update both processes and teaching methods and offer proposals designed to enhance skills for dealing with climate change. These proposals quickly reveal themselves to be complex and require interdisciplinary approaches, which have led to the development of modules that differ from more traditional subject-based courses.

This type of learning also allows students to envisage themselves in career situations and anticipate how occupations will change. From producers to advisers, all of them will be affected by climate change, each of them in their own different ways.

In a broader sense, these developments can be interpreted as "weak signals" heralding more profound changes. Firstly, they underscore the appetite among students for innovative forms of teaching that are more user-friendly and fun. Above all, they respond to a desire on the part of students – who are future industry professionals – to be more than just recipients of top-down learning and to receive support in the interdisciplinary exercise of gathering and using knowledge. Courses will be less prescriptive and more a mix of cross-cutting and top-down information, which will feed into strategic or operational thinking that must take viewpoints from a range of stakeholders into account.

This is all consistent with the vision of how professions are expected to shift, as predicted in forecast studies (Aigrain *et al.*, 2023) and by the think tank that chairs the Institut Agro Montpellier's vine and wine business group (Touzard and Hannin, 2023). The winegrowers of tomorrow will generally be connected to each other in operational, interconnected networks, able to work hand in hand with research and innovation institutes. They will not have turnkey solutions available to them, or panaceas for climate change, or "vaccines" for emerging diseases and pests posing similar threats to vineyards at the same time.

These pioneering initiatives highlight a major challenge for universities, colleges and schools offering viticulture and wine courses: in addition to lectures, they must offer educational settings that will prepare future industry professionals to operate in a context that is still largely unknown and marked by structural changes in the model of production, work and the creation of knowledge for action.

If we are to adapt to other major challenges, such as the phasing-out of pesticides, the digital transition and new global wine markets, we will also need to combine and perhaps integrate knowledge.

CHAPTER 5

PROMOTING CLIMATE ACTION AT LOCAL LEVEL: THE EXAMPLE OF WINEGROWING CLIMATHONS

Nina Graveline, Marc Nougier and Jean-Marc Touzard

Introduction

The increasing pace of climate change calls for new knowledge on climate action, which covers both the mitigation of greenhouse gas emissions and the adaptation of human activities and ecosystems (Solecki *et al*., 2018). Collective actions revolve around the local scale (Joshi *et al*., 2022), particularly in the wine industry, where product quality has been built on the concept of terroir, which encompasses local production conditions, including climate (Casabianca *et al*., 2006). For adaptation, it is important to explore, combine and rapidly implement innovations and changes that not only take into account local impacts of the climate crisis, but also talk to stakeholders who have ties to the terroir in question. Many local stakeholders are involved when it comes to reorganizing a winegrowing area and using resources such as land (the estate and its soil and climate characteristics), water and landscape features. Leveraging the breadth of their knowledge and networks is key to creating new solutions and speeding up individual and collective climate action.

This desire for openness and local action in the face of climate change prompted the European Union's Climate-KIC[42] to launch a global event in 2015 for cities wishing to host it: the Climathon. Modelled on hackathons, which are designed to stimulate creativity and group intelligence to solve a problem (usually IT-related) within 24 hours, Climathons are organized on a city-wide scale to identify solutions to climate change, such as in transport, energy or town planning. Based on the initial results of the LACCAVE project, which highlighted the importance of local adaptation strategies (Barbeau *et al*., 2015; Ollat *et al*., 2016b), we joined the Climathon initiative, and then adapted and trialled the approach across several winegrowing districts. How can the stakeholders in a winegrowing district be called into action and come together for 24 hours to develop and initiate collective actions tackling the climate challenge? What are the impacts and lessons of these experiences?

This chapter presents an approach trialled in 2018, 2020 and 2021 in three winegrowing districts in the Hérault region of south-western France. It was designed to gain insights into methods for bringing about climate action in winegrowing areas. We will begin by looking at the challenges and methods involved in encouraging local stakeholders

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[42] Climate-KIC is "Europe's leading climate innovation agency and community, supporting cities, regions, countries and industries to meet their climate ambitions through systems innovation and place-based transformations" (https://www.climate-kic.org/). It is funded by the European Institute of Innovation and Technology (EIT).

to take climate action. We will then present the Climathon approach and the characteristics of the winegrowing districts chosen. The process, results and impact of these winegrowing Climathons will then be detailed and discussed with a view to opening up avenues for their future development.

Box II-5-1. Range of participatory approaches in French winegrowing areas

As part of the LACCAVE project, a study was carried out in 2020 on participatory approaches adopted in French winegrowing areas (Gourvennec, 2021). Representatives from 180 winegrowing organizations took part in an online survey covering all winegrowing regions in France. Nearly a third said they had taken part in or were aware of participatory projects focusing on the climate issue. A total of 76 projects were mentioned, featuring different levels of participation, from the mere consultation of winegrowers to the joint creation or management of actions. A list of project types was drawn up and detailed their objectives, scale, duration, degree of openness and involvement of participants.

1. Networks for sharing knowledge and trials between winegrowers

The networks were set up to monitor varieties and winegrowing practices. They are run by economic and environmental interest groups (GIEEs), associations, groups from cooperatives, wine trade associations or product protection and management bodies (ODGs). They each have their own dynamic but can be supported by a technical or research adviser: GIEE La Clape (Aude department), GIEE/Coop Roy René (Rhône Valley), ClubMedoc (Bordeaux), Centre for the Promotion of Agriculture and the Rural Environment – CIVAM Occitanie (Occitania), GIEE Westhalten (Alsace), etc.

2. Local creative multi-stakeholder events

Organized by local authorities or winegrowing organizations, these one- or two-day events allow a wide range of stakeholders to come together and identify solutions. They comprise entertaining, creative activities: Climathons, Forum Ventoux (box II-5-3), Champagne hackathon.

3. Development of a climate strategy for the viticulture and wine industry

These projects are headed up by a wine trade association or designation association to support strategy development. Running for several months, they combine expertise, communication and workshops, often restricted to winegrowing stakeholders: CIVB, CIVC, InterRhône, InterLoire (box II-3-1), Languedoc PDO projects, etc.

4. Regional or national foresight studies and participatory research

These initiatives bring together research and winegrowing organizations (FranceAgriMer, wine trade associations, chambers of agriculture, etc.) for open, strategic and often multi-regional foresight events (LACCAVE regional forums, CLIMENVI and workshops [Loire Valley]) (box II-5-4; chapter II-7).

5. Contributions to local climate policy

Winegrowers and their organizations are involved in drawing up climate plans (known as PCAETs in France) or land management plans, albeit largely during consultation phases (the Grand Narbonne PCAET, the Rhin et Vignoble Grand Ballon PCAET, the Beaujolais landscape plan, the Haute Gironde local coherence plan [SCOT]).

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6. Participatory research/action and joint design

These research projects rely on a group of winegrowers to co-design and evaluate innovative systems or adaptation measures: Bachus workshop site (Bordeaux), doctoral thesis by Audrey Naulleau, etc. (chapter II-6).

7. Living labs and winegrowing clusters

These projects bring winegrowers, suppliers, start-ups and R&D organizations together in the long term to trial innovative technologies, equipment and services that can assist with adaptation: Occitanum project, VitiREV, etc.

8. Participatory science and crowdsourcing projects

These research-led programmes call into action a network of winegrowers providing information on the impact of climate change in winegrowing areas, depending on grape varieties and practices: the Observatoire des Saisons, the Phenoclim project, the Oscar network, etc.

Renewing participatory approaches at local level: the climate-action challenge in winegrowing areas

In chapter two of its Sixth Assessment Report, the IPCC puts forward a series of recommendations for enhancing the resilience and adaptation of human activities in response to the climate crisis. In particular, the report stresses the urgent need to develop inclusive, participatory and multi-sectoral actions at local and regional level, while also strengthening global climate governance (IPCC, 2022). Indeed, literature on climate change adaptation uses a series of arguments to highlight the importance of local community-based action and participatory approaches (McNamara and Buggy, 2017), in line with the results of research conducted in winegrowing areas as part of the LACCAVE project.

Local scale: a key to the adaptation of winegrowing areas

Six points can be made to highlight the importance of local climate action:

1. Firstly, climate change and the exposure of human activities to its risks vary from place to place. Adaptation must therefore take local climate variations into account and they must be anticipated, with varying degrees of uncertainty, depending on the methods used (Quénol, 2014). These approaches are vital to the winegrowing industry, which in France is organized in regions and terroirs where climate trends can vary greatly (Le Roux *et al.*, 2017; Ollat *et al.*, 2022), even within the same winegrowing area.
2. The impact of climate change also hinges on the resilience of ecological and social systems and is linked to local factors such as production specializations, infrastructure, institutions and knowledge (Füssel and Klein, 2006). Local grape variety characteristics, the presence of an irrigation system or advisory services, and local winegrowing practices and knowledge in response to climate risks can all have an impact on the resilience of winegrowing areas and how they adapt (Barbeau *et al.*, 2015).

3. Introducing new adaptation actions will require resources that will vary at local level in terms of type, availability and combinations. In winegrowing areas, this may involve access to land or water, features of ecosystems and landscapes, potential funding, the skills of winegrowers and other local stakeholders, etc. These resources are often local public assets (Belletti *et al.*, 2017).
4. Despite globalization, the local area remains a "lived space", a sensitive and social setting to which many stakeholders are attached and in which the climate issue can be expressed in specific, collective terms that invite action (Devine-Wright and Quinn, 2020). In winegrowing areas, viticulture and wine often have an important symbolic role to play, over and above the positive contribution they have to make to other activities such as tourism (Bertrand *et al.*, 2020). They can therefore play an important role in encouraging local climate action.
5. Formal frameworks for collective action already exist at local level, through town councils or local authorities, associations, and organizations that can help tackle the climate issue, as is the case with local climate-air-energy plans or PCAETs. There are already designation associations, cooperative wineries, and groups and associations involved in local projects.
6. Finally, over and above local resources and frameworks for action, adaptation capability is based on the activation of networks connecting local communities to external stakeholders and resources linked to other areas and more global scales (Klenk, 2017). This relational aspect is recognized as a key condition for innovation (Pecqueur and Zimmerman, 2004), including for viticulture (Chiffoleau and Touzard, 2014). This lever should also be used for climate change adaptation (Moloney *et al.*, 2018).

Participation: a critical factor for adaptation in winegrowing areas

The climate emergency is also speeding the development of participatory approaches, with varying degrees of openness and stakeholder involvement, ranging from consultation and cooperation to joint decision-making (Hassenforder *et al.*, 2021). Such initiatives are already being rolled out in winegrowing areas (box II-5-1). There are six specific points that need to be considered here:

1. Taking collective action to mitigate and adapt to climate change requires awareness and shared engagement in climate issues, along with the creation of a joint vision and narratives, which can be fostered by participatory approaches and coverage of them in the media (IPCC, 2022).
2. The sense of urgency, complexity and uncertainty surrounding the whole climate issue is also driving the collection of new data across a number of fields. Involving economic stakeholders, users and members of the public can encourage the collection of data on climate change impacts or the trialling of new solutions, thus supporting participatory science.
3. The need to explore new and more radical strategies means taking creativity to the next level, which can be achieved by encouraging stakeholder interactions to better take differing viewpoints into account (Moser and Ekstrom, 2010).
4. Public assets are commonly deployed for climate action, the use and governance of which are founded on negotiations and a commitment to society. Consultation with stakeholders in the areas where these resources are used is essential to both the effectiveness and acceptance of adaptation options (IPCC, 2022).

5. Participatory approaches and events can be a catalyst for new cooperative networks between stakeholders in different industries and regions and enhance their ability to adapt.
6. Finally, as well as justifying the effectiveness of climate action, ethical and political lines of argument emphasize the need for participation to support social change and climate change adaptation (Ross *et al.*, 2021). In France, this democratic requirement is echoed in the way winemaking institutions operate, such as protected designations of origin (PDOs), which are based on local committees operating with decisions validated at the national scale by the INAO.

Work conducted as part of the LACCAVE project encompasses points 1 (Ollat *et al.*, 2022), 2 (García de Cortázar-Atauri *et al.*, 2017), 4 (box II-5-2) and 5 (Boyer and Touzard, 2021).

Climathons as a means of identifying solutions and encouraging local stakeholders to get involved

While the climate emergency has led to the development of local participatory approaches, little research has been conducted into methods that can be implemented, particularly in rural and agricultural areas. There is a body of literature on ways of supporting innovation at regional level. It now also includes participatory approaches based on support for open innovation, innovation ecosystems and living labs (Compagnucci *et al.*, 2021). The climate issue has yet to be fully integrated into this literature. There is also a great deal of work being done on methods for providing local support for innovation or change in agriculture (Faure *et al.*, 2018), though it tends to focus on agroecological transition (Bergez *et al.*, 2019; Toffolini *et al.*, 2021). There is also a body of literature on the role of cities in climate action (Hölscher and Frantzeskaki, 2021), though little research has been conducted into citizen initiatives. There is a real need to provide references and analyses of participatory methods as a means of supporting local climate action, from creating new solutions to implementing and evaluating them.

The Climathon is based on the concept of the hackathon, which was dreamed up by IT developers. The principle is to solve a problem by bringing people concerned with it together in a friendly, fun atmosphere for 24 hours, the idea being to stimulate collective intelligence and come up with solutions. A Climathon – the word is short for "climate hackathon" – has three objectives: to raise awareness of the climate issue among local stakeholders; to strengthen local innovation ecosystems; and to inspire projects and actions in favour of the climate. Climate-KIC invites towns and cities to take part in this annual event by following the same approach:

1. Candidate cities find an "organizer" and draft a specific question designed to tackle a climate challenge such as "How can we rethink mobility to curb greenhouse gas emissions?" The question must address local climate change issues.
2. The organizer draws up a 24-hour programme that follows the format of a hackathon: getting to know one another; understanding the problem and its implications; exploring the range of solutions; choosing projects offering potential solutions; forming teams to develop these projects and then putting them out to participants and users; organizing breaks so people can enjoy each other's company; presenting projects to a panel of judges and awarding of prizes.
3. The organizers then specify the methods to be used at each stage, make the necessary preparations (rooms, meals, teaching materials, etc.) and advertise the event to get local stakeholders involved.

4. The Climathon programme is rolled in a friendly atmosphere over 24 hours, with a balance between spending time with others and working on a project. Moderators ensure that realistic solutions are developed, a wide range of participants are involved in teams, a core group of participants stays for the 24 hours, and work is documented in photos and notes.
5. Following the Climathon, the organizers pledge to bring as many ideas as possible to fruition and to provide information about the event and report on it.

Box II-5-2. Climate change adaptation and water management at regional level: the Talanoa-Water project

One of viticulture's levers for climate change adaptation is irrigation. While it cannot tackle all climate change-related risks, irrigation does help reduce or manage the effects of water stress on crops. Its use has implications for regions, however, because water is a mobile resource that many different users depend on, and its availability is restricted by climate change. This solution cannot be viewed, therefore, solely in terms of the wine industry or agriculture. Regional water management is a major challenge for society when it comes to adapting climate change. As one of the largest users of water, agriculture is heavily impacted by this challenge (chapter I-7).

Local authorities and socioeconomic stakeholders are thus looking to build and analyse water development and usage strategies, in line with various exogenous scenarios (most of them climate related) and with water regulations outlined in a local water resource management plan (PGRE), steered by a local public watershed authority (EPTB).

The approach proposed by the Talanoa-Water project is to identify and evaluate transformational and robust adaptation strategies to deal with water scarcity brought about by climate change, and to speed their adoption while contributing to the goals of integrated water resource management (social equity, economic efficiency and environmental sustainability). To achieve this, the project proposes the development of an innovation ecosystem based on an inclusive and transparent method of stakeholder engagement, using hydro-agro-economic modelling that includes the use of a serious game to explore different adaptation strategies. This approach is being developed in six Mediterranean "pilot water laboratory" watersheds.*

France's pilot laboratory is the downstream and middle sections of the Aude watershed, where irrigated winegrowing has developed and which is prone to a major imbalance between abstracted water and water demand. In 2023 (midway through the project), more than 50 agriculture and water management stakeholders took part in three workshops to discuss the current situation, create foresight scenarios for winegrowing/agricultural development, and identify four main types of measures:

- mobilizing water resources
- enhancing technologies and networks
- agroecology and agricultural practices
- regulatory and incentive instruments, and governance

An early version of a serious game was used to encourage stakeholders to discuss objectives and measures to be implemented in relation to each other and across three separate time frames: 2025, 2035 and 2050. The strategies will be assessed in 2024 with hydro-agro-economic models and stakeholders, and will feed into local authority action plans and the water resource management plan.

* Italy, Egypt, France, Lebanon, Spain and Tunisia.

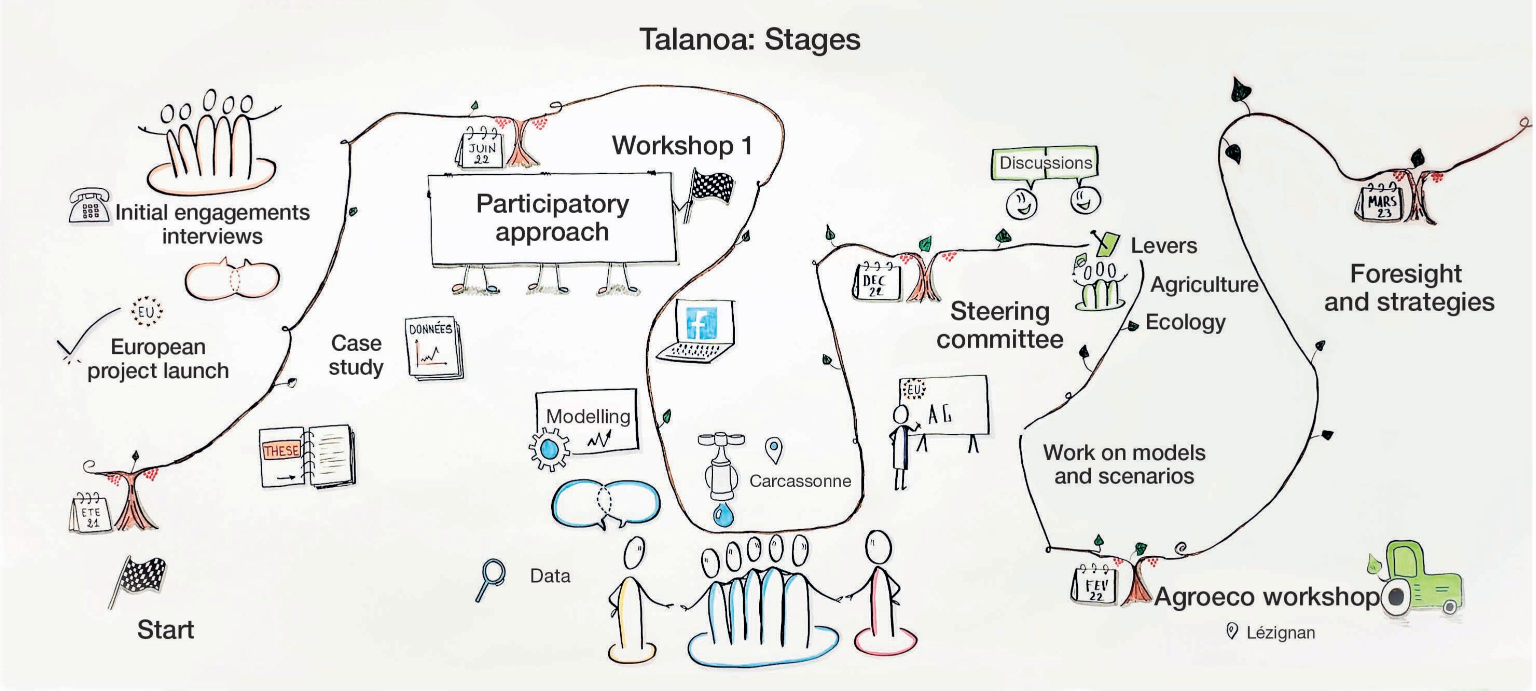

Figure II-5-1. Timeline of the major phases in the Talanoa-Water project up to mid-2023. © Sophie Banette, Isabelle Majorel, SI Facilitation, Montpellier.

Development of a Climathon method for farming communities

In adapting the Climathon method to farming communities, we drew on Climate-KIC principles and guidelines and on previous participatory experiences (e.g. the LACCAVE project). We trialled the method in three winegrowing districts near Montpellier (in south-western France) in 2018, 2020 and 2021. In addition to providing an initial methodological framework, Climate-KIC also co-funded[43] some of these events and helped improve communication of them (online platform), incorporating them into an international network of cities.

The three winegrowing districts

Moving from a big city to a winegrowing district has implications for participatory events. Natural, agricultural and winegrowing areas take centre stage, with the issues, types of stakeholders, frameworks and focal points all changing. Winegrowing, a dominant economic activity in the region, is being targeted. As a result, the stakeholders involved need to be assessed, while looking beyond their professional circle. The modest size of the districts limits the available funding for events and, above all, the number and types of potential participants. Our view in response was that while the vineyards in each district were the priority, the social space in question was more extensive and included stakeholders from neighbouring districts and researchers and students from Montpellier.

The three selected districts are located in the Hérault department (at the heart of the Languedoc winegrowing region), where a new strategy was introduced by estates and cooperative wineries in the 1980s. Once dominant, table wine has given way to fine wines with PDO protection in hilly areas and protected geographical indication (PGI) wines on the plains. We chose districts where the vines are planted on hillsides, which mainly produce PDO wines (table II-5-1). In all three districts, climate change was a cause of concern for the stakeholders we met first (wine industry representatives and town mayors). These districts are at various distances from Montpellier (between 15 and 55 km), which has a potential effect on population density, the socioprofessional categories of residents, and the size of cooperatives. In Murviel, near Montpellier, the cooperative has been disbanded, with winegrowing now organized around organically farmed estates. In Montpeyroux and Cabrières, meanwhile, cooperatives are dominant and dynamic, producing terroir wines: Montpeyroux PDO and Rosé de Cabrières PDO.

Choosing organizers and participants

In keeping with the Climathon concept, the host organization is the local council, in association with a winegrowing organization (designation association or cooperative). In the cases presented here, the initiative is supported by INRAE, which coordinates the preparatory sessions, the event and the report on it but is not especially visible and is not

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[43] Through the AWICC and MEDCLIV projects, which aim to strengthen innovation ecosystems for viticulture adaptation, funded by the European Institute of Innovation and Technology (EIT) Climate-KIC (Knowledge and Innovation Community), and headed up by INRAE (in France) and the Italian Institute of Biometeorology (IBIMET).

Table II-5-1. Details on the three Climathon districts. UAA: utilized agricultural area; FTE: full-time equivalent employees. Source: French National Institute of Statistics and Economic Studies (INSEE), general agricultural and district census.

	District	Viticulture	Wine production	Geography
	Surface area Population No. of workers Distance from Montpellier	**Vineyard area Share of UAA Wine industry workers Share of workforce**	**Estates Cooperatives PDO share, organic share**	**Altitude Average precipitation Topography**
Murviel-lès-Montpellier	1,010 ha 1,900 pop. 750 workers 16 km from Montpellier	140 ha 76% UAA 27 FTE wine industry employees 4% of workforce	8 estates (85% vol.) 12 cooperative members (15%) External cooperatives 70% PDO, 75% organic	150 m (66–236) 800 mm, falling Small hillside fields
Montpeyroux	2,242 ha 1,370 pop. 550 workers 35 km from Montpellier	620 ha 70% UAA 85 FTE wine industry employees 15% of workforce	15 estates (25% vol.) 110 cooperative members (75%) Coopérative Castelbarry 60% PDO, 20% organic	130 m (66–648) 900 mm, falling Hillsides, terraces and valley floors
Cabrières	2,900 ha 550 pop. 200 workers 55 km from Montpellier	340 ha 94% UAA 45 FTE wine industry employees 23% of workforce	3 estates (15% vol.) 56 cooperative members (85%) Coopérative Estabel 90% PDO, 30% organic	135 m (76–481) 700 mm, falling Hillsides and valley floors

necessarily a key player. In the districts in question, the local council and winegrowing organizations have shown an interest and have played a key role in designing the event, reaching out to stakeholders, managing logistics and then promoting the event.

Though aimed primarily at local winegrowers and residents, the event is open to everyone. Participants volunteer to take part by registering beforehand. This allows invitations to be extended to ensure a wide range of stakeholders are included: different types of winegrowers, representatives of local associations, elected officials, other stakeholders in the vine and wine and other industries, students and researchers.

Winegrowers are front and centre, sharing knowledge and implementing solutions, while also joining participants on tours of their wineries as part of a Climathon sequence. Another specific feature of our take on the Climathon is the inclusion of experts, who are free to make contributions on climate change, viticulture, water management, marketing channels and communication, among other areas. They are invited to make short presentations at the start of the Climathon and are then on hand to help teams develop their projects.

Wine Climathon programme and organization

The Climathon was initially organized as a 24-hour event, without a break at night, in line with hackathon rules. However, given the range of participants at this type of event, which included people from different professions and of all ages, some of whom may have children to look after in the evenings, it was never likely that they would accept the same conditions as young IT experts. We then decided to change the way the event was run, starting late Friday afternoon, before taking a break at around 11 p.m., resuming on Saturday morning and finishing late in the afternoon.

The winegrowing Climathons comprise five stages, each with their own objectives, methods and outcomes (figure II-5-1). Participants have the chance to relax and have fun in-between stages with icebreakers, wine tastings, meals, musical entertainment and prize-givings, and there are a host of situations where attendees can interact: group presentations, round tables, teamworking, the creation of a mural, collaborative sessions, team-building, field visits and presentations to a jury. These stages unfold as follows:

1. The aim of the first stage is to **share knowledge** about the chosen topic, the Climathon programme, climate change and the development of the local wine-growing area. The organizers give group presentations, with the floor then opened to questions.

Box II-5-3. Ventoux case study: from climate change adaptation issues to its raison d'être

In the Ventoux valley, and particularly its winegrowing areas, a considerable amount of thought has been given since late 2017 to the consequences of climate change, which is becoming increasingly noticeable in the region. This whole process has prompted the Ventoux ODG to ask INRAE (Agroclim unit) to assist and provide input. In an initial phase, the nature of past, present and future climate changes were identified. The results revealed recent changes, with a significant increase in phenological advance and a sharp rise in temperatures during fruit ripening. These trends are set to intensify in the years ahead, the degree of which will depend on emissions scenarios (Marjou and García de Cortázar-Atauri, 2019). New questions have also arisen with regard to the spatial organization of vineyards and new areas that could be favourable for wine production in the years to come. A second, more detailed analysis explored the spatial structure of potential impacts (not least frost and heatwaves), particularly in areas where there is potential for expanding vineyards (Huard, 2021). This information allowed the ODG to build up a knowledge base and make a series of projections for the development and adaptation of its vineyards.

A major local initiative was also launched with the aim of understanding how agriculture in the Ventoux region could adapt to future climate conditions. Collective actions such as an Open Forum and world café involving the Ventoux ODG, the local chamber of agriculture, the Ventoux Regional Nature Park, the Ventoux Comtat conurbation (COVE), the local agricultural college, and INRAE were organized and led to the emergence of questions on mitigation, crop diversification, water management and the development of agroforestry. A number of joint projects were set up to respond to these questions. The Ventoux ODG has decided to take the long view to adapting its winegrowing areas to climate change, setting out its own raison d'être, which defines the long-term project that is the basis of its corporate purpose. Three objectives have been set for 2030:

- To protect and develop woodland
- To reduce the impact of climate change and adapt to it
- To share in and nurture local life

This should allow the Ventoux ODG to create a strategy for adapting to the various local and global challenges, in collaboration with its regional partners.

Table II-5-2. Main stages, methods and outcomes proposed for wine Climathons. *Not implemented in all cases.

Objective	**Stages**				
	1. Welcome – situation analysis	**2. Exploration of problems and solutions**	**3. Development of projects**	**4. Project maturation and discussions with experts/visits**	**5. Pitches and wrap-up**
Method	Presentations	World café	Teamworking		
	"Climate change and its impact on the viticulture and wine industry" First-hand accounts of adaptation practices	Vote Groups choose which projects to work on	Guide to issues and items for clarifying projects Short presentations	Field and winery visits Sharing of views following visits	Project presentations (open format) Jury*
		Documents and maps made available in the workshop			
Social activities	Icebreaker	Wine tasting and dinner	Break (refreshments, yoga, etc.)	Meal, music	Closing remarks and prizes
Products	Expert presentations and notes	Notes from the world café – The solutions vine	Photos and notes from visits Description of project V0	Description of project V1	Presentations (various media)
					Evaluation - report

2. In the second stage **problems and solutions are explored**, with viewpoints being expressed and cross-pollinated. The focal point for this stage is a world café[44] comprising three 20-minute sessions. Participants identify as many problems as they can as part of the Climathon challenge before picking out specific issues, examining the ins and outs, and coming up solutions to deal with them. Each group chooses a different route after the second session. The outcomes are put up on a wall to create an original "solutions vine".
3. The focus of the third stage is to whittle down **contributions to projects** that offer concrete solutions. They are selected through a vote (two votes per person) and then put forward by groups, who start organizing them, potentially with the help of experts. Pre-projects are the subject of collaborative sessions at the end of the evening.
4. In the fourth stage, **project leaders face the realities of implementation** while in the field. This involves members of the various project groups making field visits to winegrowers or wineries. The stage ends with a session in which lessons learned from the visits are shared, followed by a group meal.
5. In the final phase, **the projects are developed further and then presented** to a jury. Groups work on their projects by putting together an action plan and outlining the necessary resources. They then create a pitch, which can take the form of a presentation, sketch or video, and present it to participants and a jury, which awards prizes.

In contrast to the initial Climathon proposal, there is no overall winning project. The aim is to create a range of non-exclusive projects and initiatives, with prizes (baskets of gourmet products and local wines) to be shared among the teams.

Wine Climathon results

The results of the three Climathons can be presented together to allow an initial comparison of the facts. These results concern the drafting of the initial questions, the types of participants, proposals for action, the projects selected and developed, and an initial impact assessment.

Initial questions and local climate issues

Not surprisingly, the questions drafted by the organizing committees of the three Climathons are very similar:

- "How can Murviel use local resources to combat climate change and support its vineyards and winegrowers?"
- "How can Montpeyroux's vineyards and winegrowers survive in the face of climate and societal change?"
- "How are people in Cabrières working together in their bid to protect their winegrowing heritage and landscape against climate change?"

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[44] A world café is an environment that encourages collective intelligence. One person (ideally representing the organizers) should stay at each table for the duration of the world café, with participants changing tables at the end of each session.

These questions give voice to a defensive approach ("support", "survive", "protect") to the perceived threat of climate change and express a desire to include all winegrowing stakeholders. In terms of issues, there are nuances. Montpeyroux talk of "societal expectations", while the landscape is a cause for concern in Cabrières, a district heavily committed to the wine tourism industry.

Introductory presentations, reactions and the first world café on these issues revealed that perceptions in the three districts are similar regarding the impacts of climate change: earlier harvests, lower yields associated with growing water deficits, higher alcohol content, increased risks due to heatwaves, heavy precipitation and fires. Each district has its own pressing issues: drought in Murviel, climate hazards in Montpeyroux and the promotion of wines in Cabrières. These differences can also be explained by contexts that change each year: heatwave in 2019, a more challenging wine market in 2021.

Participants

The different types of participants are a result of the event (table II-5-3). There were 60 in total in Murviel, 38 in Montpeyroux and 31 in Cabrières. In terms of the actual participant breakdown, there were around 15 winegrowers at each gathering, including heads of cooperatives and PDO associations, as well as mayors and local councillors, and representatives of other stakeholders. Wine merchants, oenologists and other stakeholders from further downstream in the industry, often from different districts, made up a much smaller proportion. The large share of non-viticulture stakeholders in Murviel (57% in all) reflects the social structure of an outlying district and its proximity to a large city, which is more likely to be home to participants such as students. Not all participants were able to attend events in their entirety, due to family or work commitments.

Table II-5-3. Socioprofessional background of wine Climathon participants.

Participants in each district	Murviel	Montpeyroux	Cabrières
Number of participants	60	38	31
Winegrowers, from:	14	15	14
estates	10	7	3
cooperatives	4	8	11
Winemaking organizations	8	3	3
Wine merchants, oenologists	4	1	1
Researchers	10	8	4
Students	8	3	1
Elected officials	3 (including one mayor)	3 (including two mayors)	5 (mayor, deputy mayor, etc.)
Other stakeholders, local associations	13 (six associations)	6 (two associations)	5 (two associations)

Range of proposed actions

The world café sessions yielded a total of 85 proposals for action: 34 in Murviel, 24 in Montpeyroux and 27 in Cabrières. The proposals formed part of a mural of a vine stock and grouped together into "bunches" of solutions, each in different areas of action (table II-5-4). Ten areas of action were selected, most of which were highlighted in the three districts, such as water management, trialling new grape varieties, agroecological practices (soil, grass cover, etc.) and the publicizing and promotion of wines. Some areas were not included, such as growing specification changes in Murviel and mitigation actions in Montpeyroux and Cabrières. Others were specific to a district, such as carbon offsetting in Murviel, oenology in Montpeyroux and political action in Cabrières. These variations may have something to do with vineyard priorities (the importance of organic winegrowing and soil-related concerns in Murviel), but may also be the result of the types of participants and the role played by certain people (proponents of ideas, volunteers, etc.) or interaction sequences (extended discussions on a specific theme).

Table II-5-4. Number of solutions in each area of action and participant votes.

Area of action	Murviel		Montpeyroux		Cabrières	
	Number of actions in each area and share of the votes (%)		Number of actions in each area and share of the votes (%)		Number of votes and group vote (++)	
Water knowledge and management	5	24	3	19	4	++
Promotion and communication	4	6	3	4	3	++
Greenhouse gas mitigation/offsetting	10	19	1	5	1	
Development of agroecology	5	17	5	8	2	
Experimenting with new grape varieties	3	17	2	28	5	
Winemaking practices	0	0	3	4	1	
Introduction of animals	2	10	2	13	2	++
Diversification	2	3	2	15	1	
Specification changes	0	0	1	5	2	
Political action, local activities	2	8	2	0	6	
Total	**34**	**100**	**24**	**100**	**27**	**Not relevant**

Projects selected and developed by the teams

Projects were selected on the basis of a vote on the solution bunches, with ballots being held in Murviel and Montpeyroux, and a group vote in Cabrières (table II-5-4). These votes indicated the importance given to a topic, regardless of the number of initial proposals. Project starting points also depend on whether or not groups were set up to work on a particular topic. In Montpeyroux, for example, irrigation was voted for in the ballot but did not progress beyond the pre-project stage due to a lack of volunteers to develop it. One possible reason could be that the scope and technical nature of the solution was too great or complex, or that it was being covered in other areas. In total, 13 projects were started: six in Murviel, four in Montpeyroux (one of which did not reach completion) and three in Cabrières (table II-5-5). The projects were developed in line with the Climathon stages and in some cases led to original final presentations (plays, videos, etc.) and detailed notes, which were included in the summaries produced and published at the end of the Climathon (Nougier and Touzard, 2018; Nougier *et al.*, 2020; Graveline *et al.*, 2022).

Some projects were common to two or three districts:

- access to water, with a focus on knowledge of available resources and comprehensive approaches at regional level, exploring different combinations of solutions (reuse of treated wastewater, finding or rehabilitating springs, hill reservoirs, soil and landscape management, water-saving practices, etc.);
- the reintroduction of animals (sheep, goats, horses) to winegrowing areas to perform a range of services (grass cover and soil management, fire prevention, etc.), with the original idea of creating a "communal stable" being posited in Montpeyroux;
- the sharing of local knowledge about the adaptation of new or old grape varieties and management methods pertaining to them, through a communal field (Murviel) or a monitoring network (Montpeyroux).

The other projects were specific to each district, although the themes they dealt with were mentioned in the exploratory phase at all three Climathons: Murviel proposed developing a cooperative for the use of agricultural equipment (CUMA), the idea being to pool equipment and reduce the carbon footprint, as well as creating a wine forum for discussing climate issues with the public, and a local label promoting the actions of winegrowers who are offsetting climate change impacts; Montpeyroux came up with a crop diversification project on winegrowing estates (pulses, fruit, vegetables, aromatic herbs, etc.), a plan that involves the creation of new sectors in the cooperative; while Cabrières suggested a promotion drive for its wines, with collaboration between the cooperative and a prestigious estate.

Feedback and initial ex-post evaluation

In the questionnaires distributed at the end of each Climathon, participants expressed their overall satisfaction, noting that they acquired new information, engaged with new stakeholders, enjoyed the openness and friendliness of the event, and learned about new facilitation methods. There were questions about the continuity of the projects presented, their feasibility and the cost of the event in relation to its potential impact.

There was significant coverage of the events in local newspapers, not least the Murviel Climathon (*Midi-Libre*, *La Gazette de Montpellier* and *Paysan du Midi* to name but three). Features were published in town newsletters and on local and international social media accounts (including those of Climate-KIC, Vineas [box II-5-5] and the FAO). The Murviel Climathon was also featured in a documentary on climate change adaptation in winegrowing areas.[45] Three reports were published and promoted by the Occitanie Climate Change Study Network (Graveline and Touzard, 2021).

Follow-up interviews with local authorities in 2022 and 2023 give an initial idea of the impact, which varied between Murviel on the one hand, and Montpeyroux and Cabrières on the other:

- With its long history and the size of the event (number of participants, significant media coverage), the Murviel Climathon had a dynamic all of its own. Headed up by the local chamber of agriculture, a soil and climate change adaptation GIEE was

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[45] *Vignes dans le rouge* ("Vines in the Red"), a documentary by Christophe Faugère, trailer shown on https://www.imagotv.fr/documentaires/vignes-dans-le-rouge.

Table II-5-5. Projects developed at Climathons and ex-post evaluation in 2023. NP: not provided, data missing; GIEE: economic and environmental interest group; GEMAPI: management of aquatic environments and flood prevention.

	Problems identified and addressed	**Projects presented** ***Evaluation in June 2023***
Murviel (26–27/10/2018)	Water stress and drought affecting yields and wine quality	1. Hydraulic analysis and integrated water management in Murviel *2021 study, Reuse, living lab project.*
	Managing grass cover and adding organic matter to the soil	2. Bringing animals back to vineyards *Completed and extended, began before 2018*
	Trialling of new varieties and sharing of observations	3. Communal trial field *Completed, heritage varieties, planted in 2022*
	High carbon footprint of wine-tourism bottle sales	4. Local “Your climate” label and certification *Not carried out, idea backed by the local authority*
	High logistical costs (equipment, bottles) and carbon footprint	5. Pooling of equipment to reduce carbon footprint (CUMA) *Initiative not developed*
	Sharing wine challenges and knowledge in a context of climate change	6. Murviel public forum *Other project types (GIEE, third place)*
Montpeyroux (6–7/03/2020)	Water stress and drought	1. Integrated water management *Incomplete, study to follow*
	Maintaining income and limiting climate risks	2. Diversify to adapt *Idea adopted at individual level*
	Sharing of information on varieties and practices	3. The winery of the future: a trial experience *PDO association project*
	Managing grass cover by reducing the carbon footprint	4. Setting up a vineyard stable *Not implemented*
Cabrières (15–16/10/2021)	Failure to promote wines effectively	1. Collective communication and promotion tools (video, film, series, etc.) *NP (planned by group of district councils)*
	Water stress and drought, no access to water	2. Status of the district’s water resources, etc. *NP (planned with the Institut Agro)*
	Risk of fire and soil and landscape degradation, risk of flooding due to lack of maintenance of the Boyne River	3. Introduction of a herd of goats to aid weed control, fertilization and the clearing of ditches and undergrowth to prevent fires, etc. *NP (planned in GEMAPI framework)*

set up and extended to other districts to the west of Montpellier. A goat farmer is now practising conservation grazing in his vineyards, having set up to do so at the time of the Climathon. A study was conducted in 2021 on the history of water management in the district, which subsequently applied for living lab support for a project on circular water use. In 2022, a communal field was planted with heritage grape varieties as part of a trial. Thanks to a third-place project involving winegrowers, a building that was once home to a cooperative winery is being renovated.

– The projects undertaken in Montpeyroux and Cabrières, which are more recent but were affected by the Covid-19 pandemic, have yet to produce results. However, there have been a number of individual (crop diversification) and inter-district (new wine and climate events) initiatives. In the opinion of the chairpersons of two cooperatives, the Climathons have led to stakeholders getting involved in other projects and have helped to "move ideas forward". These examples highlight the need for one-off events such as Climathons to form part of a longer-term approach driven by local stakeholders and involving a range of activities and processes.

Box II-5-4. CLIMENVI: integrating climate change into the decisions made by winegrowers in the Centre–Val de Loire region

The aim of the CLIMENVI European Innovation Partnership (2018–2023) was to develop training and advisory tools to help winegrowers understand the impact of climate change in the Centre–Val de Loire region. CLIMENVI was founded on three pilot ventures with technical and financial features representative of the region and located in three PDO areas (Chinon, Touraine and Sancerre).

Based on a study of changes in agrometeorological variables, socioeconomic contexts and adaptation pathways at the three pilot sites, three tools were developed:

- A training module
- The CLIMENVI-App, a decision support tool
- A free informational brochure

The realistic adaptation pathways designed in conjunction with winegrowers considered three time frames: short term (the current year), medium term (2030) and long term (2050). They encompass four areas of adaptation: terroir and planting matter; viticulture; harvesting and winemaking; and the organization of vineyard work.

The short-term analysis revealed that a large number of actions have already been implemented in response to climate variability. No sense of panic or urgency was noted: "We have had upheavals before," said winegrowers, who were confident and proactive in the search for solutions. While the need for equipment was not identified as the main obstacle to adaptation, the challenge of adopting greening practices added to a greater need for labour at certain times of the year, are central to the socioeconomic problems faced by winegrowers. Global warming has, for the time being at least, also led to an increase in the frequency of good vintages, particularly for reds. The main technical adaptation levers are effective protection against spring frost and sufficient cooling capabilities for the harvest period. One ongoing obstacle, however, is access to knowledge about climate change, which is necessary in anticipating reorganization of labour activities. Expectations are high, for example, in terms of the ability to prevent extreme weather events. Finally, uncertainty still surrounds consumer acceptance of changes in wine typicity. Many winegrowers have expressed a real need for support.

Conclusion

These wine Climathons show that local stakeholders can be called into action to work on local climate adaptation projects over a 24-hour period and – it can only be hoped – encourage awareness and climate initiatives to be undertaken in winegrowing areas.

The benefits and limitations of wine Climathons

Winegrowing Climathons are popular with participants and allow solutions to be explored and projects to take shape. Communication of these events and the impact they have in terms of new partnerships and projects also point to the success of the approach, although we cannot make assumptions about the long-term effects.

As more than just social events with much to offer participants, winegrowing Climathons have three main benefits:

- By connecting stakeholders from different socioprofessional backgrounds, they offer something new, amounting to much more than just a meeting of winegrowers or between winegrowers and wine consumers. This "open" approach is one of the benefits of Climathons and encourages a range of solutions and, above all, the involvement of winegrowers in local climate actions. These events are part of the process of supporting open agricultural development innovations (Faure *et al.*, 2018) and territories in transition (CLER, 2021).
- They must be analysed in the light of the processes and projects being carried out by local stakeholders. Above all, they provide a platform for, accelerate and enable initiatives that are already under consideration or are being carried out by stakeholders, as the Murviel event showed. Our analysis confirms that Climathons give visibility and support to action that is already being taken, in both urban and rural areas (Ross *et al.*, 2021; Simmonds *et al.*, 2022).
- The value of Climathons must also be measured beyond their local impact. Communication around events, publications and the sharing of experiences in winegrowing, political, scientific and community networks are all boosting climate action in French winegrowing areas and the bottom-up process called for by the IPCC (IPCC, 2022).

The limitations of winegrowing Climathons should also be noted:

- They are one-off events and there is no guarantee they will have the desired effects, which are difficult to evaluate in any case.
- While a range of stakeholders is vital, attracting them depends on interest, motivation and availability, which can vary greatly from one district to another.
- The amount of time and knowledge available can limit the development of projects presented, which sometimes leads to more emphasis being put on the way in which they are presented than on depth or relevance of content.
- Climathon participation and output depend on circumstances, with potential threats such as Covid-19, which restricted the scale of the Montpeyroux Climathon (held on the eve of lockdown).
- Lastly, whether or not local stakeholders take these approaches on board remains dependent on the involvement of scientists, echoing criticism of the difficulty of empowering participatory approaches to agroecological transition (Bergez *et al.*, 2019).

Conditions for staging a successful wine Climathon

By looking at the benefits and limitations of wine Climathons, we can draw certain conclusions on how to ensure their success, in line with recommendations put forward by Climate-KIC or presented in literature on "citizen co-production" (Mees, 2022):

- First, it is good to have a broad range of participants, striking a balance between the various of categories of stakeholders who are represented, participants' complementary skills and motivations, and "legitimate" stakeholders and less visible or even "fringe" stakeholders. Targeted, and in some cases repeated, invitations are needed to attract a truly broad cross section of willing and motivated stakeholders and avoid creating an echo chamber.
- Preparation is key and will require a significant time investment and sufficient funding. Our feeling is that having a local politician or winegrower familiar with local conditions of participation involved in the event can go a long way, and it is important to have a range of stakeholders from different socioprofessional backgrounds.
- Allowing time for collaborative work, socializing and field visits seems to encourage participation during the Climathon, while some urban Climathons feature online sessions (Simmonds *et al.*, 2022).
- During events, moderators and moderation methods are key to encouraging interaction, with efforts focused on making the objectives and limits of the exercise clear, building trust and a common language, and keeping to schedules (while allowing a certain amount of leeway to make adjustments). This is a skill that cannot be improvised and must be planned for in advance, either within the organizing team or by calling in external consultants.
- Finally, post-event communication, reports and publications, and the involvement of elected representatives, engaged citizens, scientists and winegrowing organizations in the projects proposed play a major role in making the event part of longer-term local development processes and encouraging replication in other areas. This "post-production" phase should not be overlooked.

Box II-5-5. Vineas: a collaborative viticulture, wine and climate change platform

Vineas.net is a collaborative platform that brings stakeholders, initiatives and knowledge together in an effort to tackle climate change in the viticulture and wine industry. It is open to everyone but is particularly well suited to anyone supporting the adaptation or mitigation strategies of industry stakeholders such as advisers, trainers, project leaders, technicians and researchers who produce knowledge, often together. One of the platform's main aims is to enable knowledge production and sharing between stakeholders in winegrowing regions that may be far apart, but which can take cues from similar climate conditions elsewhere or anticipate changes in their climate.

The platform is organized around seven categories of data or content:

- identifying **actors (institutions)** concerned with these issues and highlighting of their **projects**;
- gaining visibility as an **active member (individual)** of the platform and being able to **contact** other members through a secure interface;

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- navigating and contributing to the range of **solutions and levers** (with fact sheets presenting a group of scientifically validated solutions and specific solution documents);
- making all **documents** available, from scientific literature to videos and broadcasts of events, which together provide a key knowledge base encompassing anything from local expertise to research;
- providing information and keeping abreast of the **latest news** on the subject and the **media**, plus a one-click function for uploading articles on the subject;
- providing visibility and keeping abreast of all **events**;
- posting questions, ideas, requests to share experiences, and the like in an **"agora"** designed for **interaction** with the community.

Vineas is the online version of a wider innovation community ecosystem focusing on adaptation and mitigation issues in the viticulture and wine industry. Like many other platforms, Vineas needs to be supported by other components if this ecosystem is to be brought to life through face-to-face events, newsletters and specific projects.

Vineas was initially developed as part of the Mediterranean Climate Vine & Wine Ecosystem (MEDCLIV) project, funded by the European Union's Climate-KIC. In particular, it helps to promote the work carried out in the LACCAVE project and many others run by European wine-producing countries. The platform is supported by a steering committee and scientific advisory board comprising around 20 people, and institutions, including the International Organization of Vine and Wine (OIV). Scientists are responsible for drafting and approving fact sheets for generic solutions and levers. Indirectly, this scientific advisory board is also an arena for cooperation between European scientists working on the topic from a range of perspectives.

Find out more

Video: https://www.youtube.com/watch?v=oM5AX0nlVPs

"About Vineas" section of the Vineas website: https://www.vineas.net/fr/7_24/602ba45e98bb6a1a8eab39b7/a_plataforma.html

Building participation into a new engineering approach to winegrowing terroirs

The three wine Climathons revealed the importance of participatory approaches to the engineering of winegrowing terroirs. Participatory approaches can be linked to the use of data analysis and climate simulations, diagnostics (terroir, wineries) and the running of trials with winegrowers. As the Climathons showed, participatory approaches can be used to brainstorm ideas for collective adaptation projects and for setting out project characteristics. Climathon outcomes must then be applied to other ventures and projects. The renewal of winegrowing terroir engineering can help with the implementation of "participation engineering" approaches already developed for water and land management (Hassenforder *et al.*, 2021) and support agricultural innovations (Prost *et al.*, 2017), or which have been integrated into living lab-type systems (Toffolini *et al.*, 2021). These efforts can bring the worlds of research and enterprise together with local stakeholders so that potential adaptation solutions can be trialled on a regional scale.

CHAPTER 6

MODELS FOR A PARTICIPATORY APPROACH TO DESIGN AND EVALUATE LOCAL ADAPTATION STRATEGIES

Audrey Naulleau, Laure Hossard, Christian Gary and Laurent Prévot

Introduction

Models are ideal tools for studying the impact of climate change on viticulture, as shown by the studies presented in the opening three chapters of this book. It seems worthwhile, therefore, to use them and interact with stakeholders in doing so, as it allows the information they provide to be integrated into local evaluation adaptation strategies. In return, stakeholders can be given digital information useful to the creation and implementation of relevant and effective strategies. We begin this chapter by looking at the use of models in climate change adaptation, in the specific context of a winegrowing region. We will then present a study conducted as part of the LACCAVE project, during which we developed and implemented a participatory modelling process with stakeholders in a Mediterranean winegrowing watershed. The aim of the study was to co-create and assess locally relevant adaptation strategies that can be assessed using models. Finally, we will draw lessons from this study and consider the development and use of models for the benefit of stakeholders.

Mechanistic models: essential but not enough on their own when contemplating climate change adaptation

One of the main challenges of climate change in agriculture is to forecast future production conditions and thereby enable systems to be adapted without making them more vulnerable (Mosedale *et al.*, 2016). Climate sciences provide regionalized climate sequences and indicators on trends in climatic conditions through to the end of the century.[46] Mechanistic models are then used to translate these changes in conditions into impacts on agricultural systems and how they operate (e.g. crop growth, water infiltration, the spread of pests), by gauging mechanisms and processes at plant and soil level.

Models forecasting climate change impact in the long term

In viticulture, mechanistic models (chapter I-1) can be used to predict the impact of rising temperatures on the vine's phenological cycle (Morales-Castilla *et al.*, 2020), the impact

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[46] Contribution of Working Group I to the IPCC assessment report, with some data for France available at http://www.drias-climat.fr.

of changes in precipitation on the water balance (Pieri *et al.*, 2012), and the impact of these two variables on yield and berry quality (García de Cortázar-Atauri, 2006).

Vines are perennial plants and are managed at field level by combining different timescales (figure II-6-1). The adaptation of the vine depends on bioclimatic variables and practices spread over three periods: the vine's lengthy lifespan (several decades), characterized by a regional climate and strategic planting decisions; the cyclical nature of the growing season (a year), marked by the vine's phenological cycle and by practices linked to production conditions in previous years and the current one; and the shortness of the period in which tactical decisions are made in response to weather conditions (a day to a few weeks). Thanks to the large number of virtual trials they permit, mechanistic models can be used to explore combinations of practices and climatic conditions on different timescales, assisting with the design of crop systems that meet the challenges of climate change in the short and long terms.

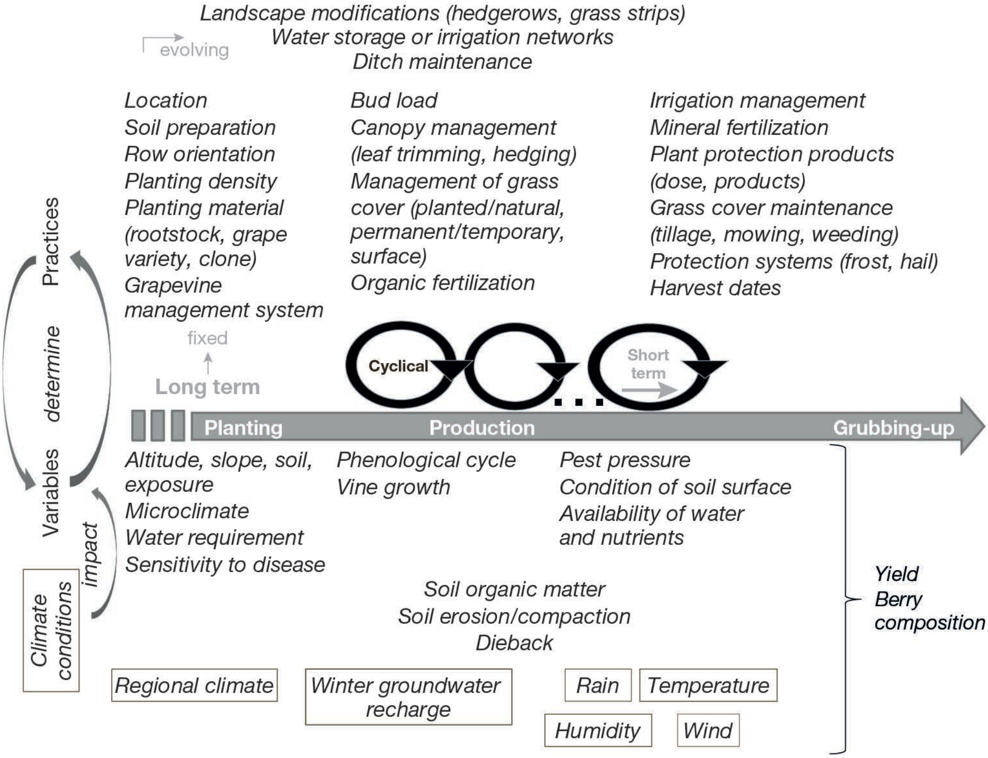

Figure II-6-1. Impacts of climate change and practices on a winegrowing system, according to the three stages of the vine life cycle (long, cyclical and short). Source: Personal communication, A. Metay.

However, large databases are needed to use these models and care is required in interpreting their results (Van Leeuwen *et al.*, 2013). First of all, most of the models used for vines are adapted from annual crop models and do not always take long-term effects into account, such as dieback or successive cycles of water stress. Secondly, the uncertainties associated with the parameterization of models, input data and greenhouse gas emission trends complicate the analysis of climate change impacts. Furthermore, these models do not take into account the effects of extreme events occurring a few hours a day, such as heat peaks, hail or frost, the frequency of which is likely to increase in the future. The validity of each model thus needs to be specified.

Models representing broad spatial variability

Climatic conditions and practices not only vary over time, but also in terms of space, greatly so and particularly in viticulture. It is common, therefore, to find very different soil and climate conditions and cropping systems in a small area, to which wine, the end product, is highly sensitive. This diversity between one location and another is mirrored at farm level, where several production strategies may coexist, depending on the terroir, water access or marketing channels (cooperative/individual wineries, labelling). This spatial variability is a lever for adapting to climate change, especially when it means diversifying sources of income, moving to locations with cooler climatic conditions (altitude, exposure) or gaining access to irrigation. Spatial models can provide a detailed representation of just such a lever.

Models can adopt the spatial scale of a single plant, field, farm, watershed, region, country or the world. The choice of this scale will determine the level of detail in the model and the data required. At best, climate data is provided for grids covering around a hundred square kilometres. Work is under way to break these climate series down to a finer scale so that microclimatic effects can be taken into account (Le Roux *et al.*, 2017). There is also some pedological data for grains of varying fineness, depending on the winegrowing region in question. However, information on cultivation practices (such as grape variety, pruning, year of planting), and performance (e.g. yield, cost, the product in its natural state) is generally more difficult to obtain over large areas. This is why climate change adaptation modelling also requires the participation of local stakeholders, especially to ensure that local terroirs and practices are better represented and that the potential for adaptation can be identified.

Models that can be used to help local stakeholders in designing adaptation strategies

Within a given area, there are opportunities and constraints that determine why, how, where and when to put levers into action. The design of climate change adaptation strategies that make sense on a local level involves coherent and interconnected combinations of adaptation levers to promote synergies and eradicate constraints between levers. These synergies are situated at a point where a number of regional scales overlap (figure II-6-2). For example, the installation of irrigation at field level is dependent on the development of regional irrigation network or storage facilities. This "irrigation" lever depends on the farm's organizational, financial and material ability to invest in such equipment. Study of these interactions thus requires a territorial approach (Chopin *et al.*, 2017), the territory being identified as the place where biophysical processes, cultivation practices and stakeholders interact. Crop systems are distributed according to the following variables: physical (e.g. soil type, topography, hydrography), technical (e.g. irrigation network), and institutional (e.g. appellation).

Evaluating territorial adaptation strategies leads us to question the role of stakeholders in the modelling process. They can be asked to describe their particular area and provide

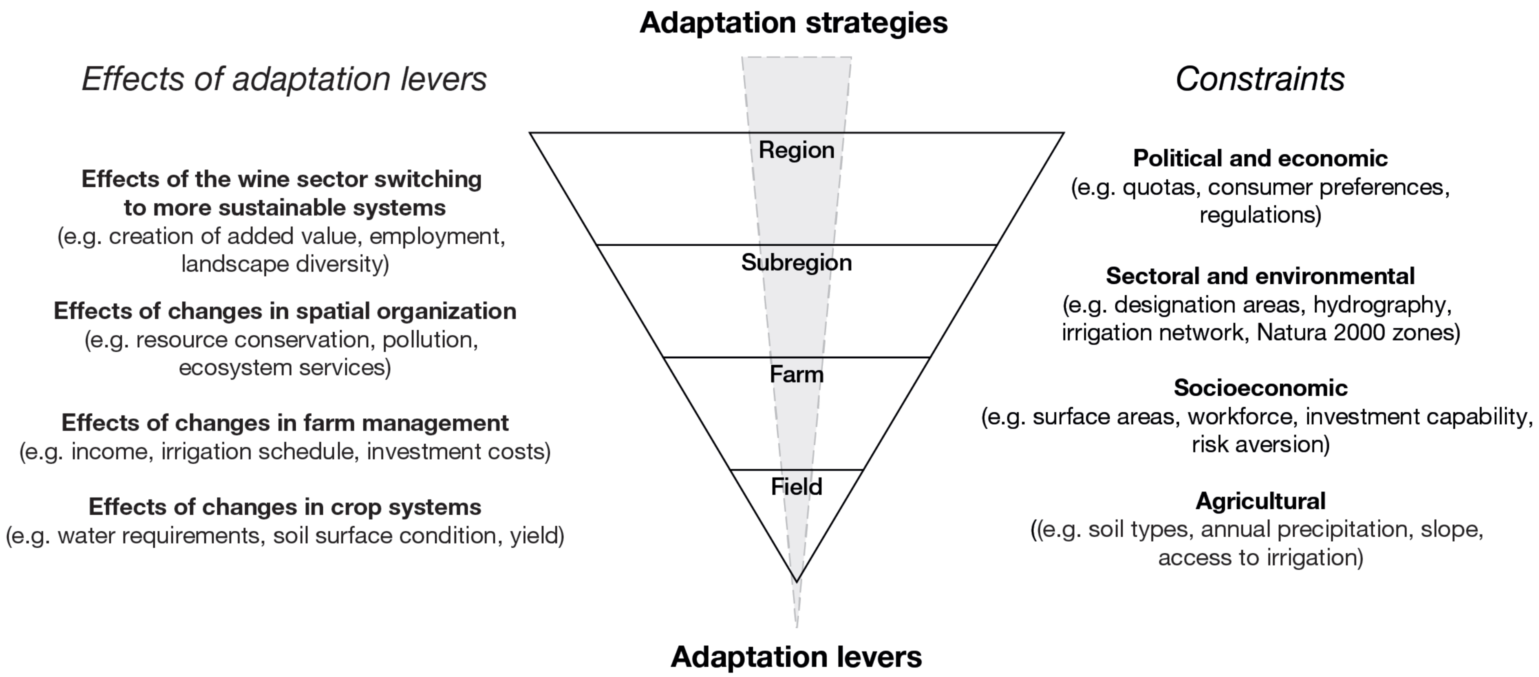

Figure II-6-2. From levers to adaptation strategies: taking effects and constraints at different regional scales into account. Based on Chopin *et al.* (2017).

information that is not otherwise available, such as winegrowing practices, actual yields, etc. but they can also assist with challenges and play a more collaborative role in the modelling process. The model can then be built with a range of stakeholders and its quantitative results discussed and expanded upon. The resulting strategies can lead to specific action plans that will require trade-offs between one issue and another.

Using models to shape stakeholder thinking in a Mediterranean winegrowing area

The study presented below formed part of the LACCAVE project. Implementing a participatory modelling process for stakeholders in a Mediterranean winegrowing watershed, it assesses jointly designed adaptation strategies using an ad hoc mechanistic model.

Presentation of the study

Located 15 km north of Béziers, the Rieutort watershed (45 sq. km), a tributary of the Orb river, is home to vineyards covering 1,500 ha, which amounts to 80% of the cultivated area (CAP, 2017), and some 136 farms. It lies at a point where the Béziers plain to the south meets the slopes of the Saint-Chinian and Faugères PDOs to the north (figure II-6.3):

- Some 20% of the vineyards are located on schist-covered slopes to the north, where fields are grouped together in islets surrounded by forests or *garrigues* (scrubland ecoregions). Vines are commonly planted on south-facing slopes and are sometimes goblet-trained. Target yields vary between 30 and 45 hL/ha.
- Some 60% of vineyards are located in the central clay-limestone zone, where fields are often laid out in the form of what are known as *terrassettes* (small terrasses). Extremely heterogeneous, target yields in this sector range from 45 to 90 hL/ha.
- Some 20% are situated on the alluvial plain to the south, where fields are large (over 1 ha) and flat. Most of the vines here are drip-irrigated. Target yields often exceed 90 hL/ha.

The process comprises three phases, each involving the participation of stakeholders in the watershed under study (figure II-6-4). In the first phase, the model is built, with participants coming together to create a conceptual diagram, then implemented by developing the digital model. The model is tested in the second phase. The test comprises three stages, starting with a description of the reference situation, followed by an analysis of the model simulations, which is both quantitative (agricultural monitoring) and qualitative (workshop-based). Following stakeholder validation of the first two stages for the historical period (1981–2010), the third stage involves simulating this same situation in future climate scenarios and then creating adaptation strategies, which are in turn simulated and analysed in these future scenarios.

In practical terms, the process was organized into five participative workshops, interspersed with modelling phases. Local and regional stakeholders (table II-6-1) were encouraged to share their perceptions of the impacts of climate change and the actions envisaged; describe the local diversity of winegrowing systems (reference situation) and identify assessment indicators; discuss the results of simulations in future climate conditions; build adaptation strategies; and discuss adaptations and their performance.

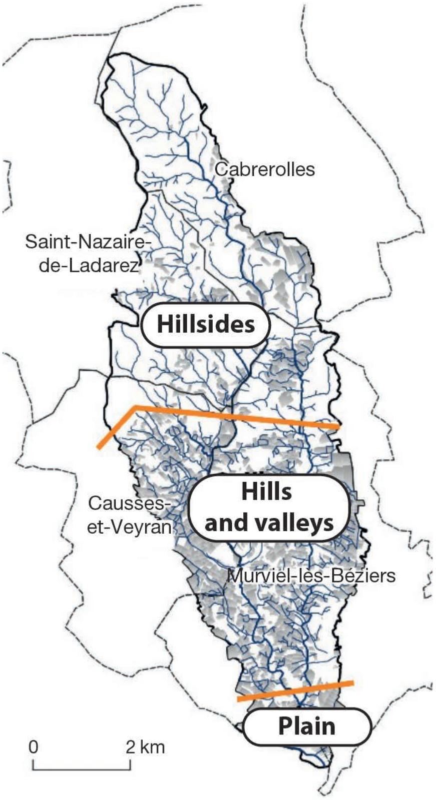

Figure II-6-3. Rieutort watershed. Vineyards are shown in grey, the river system in blue, and municipal boundaries in dotted lines.

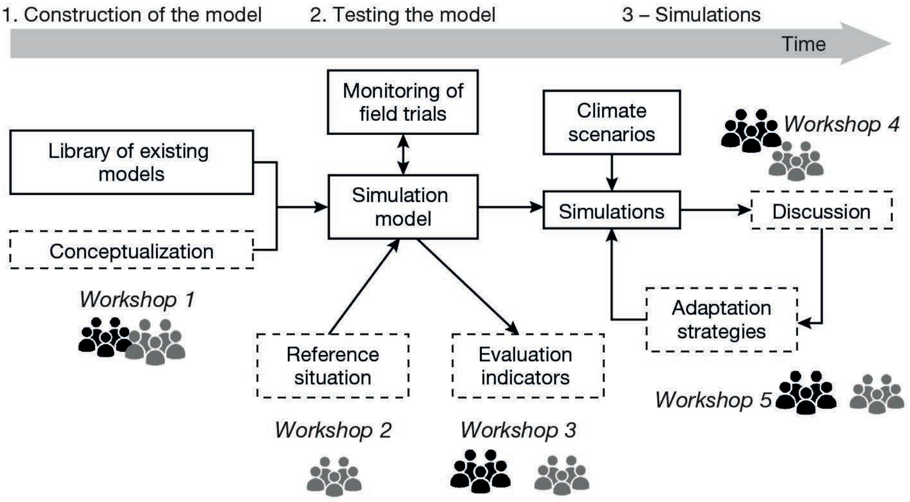

Figure II-6-4. General presentation of the method. Activities carried out with stakeholders are shown in dotted lines, while those carried out by researchers are shown in solid lines. The group of local stakeholders is shown in grey, while regional stakeholders are shown in black.

Table II-6-1. Stakeholders involved in the process. Average number of participants shown in brackets.

Sectors	Local scale	Regional scale
Wine	Winegrowers (independent and cooperators) (4) Cooperative winery (1) PDO associations (2) Support and advisory service (2)	Support and advisory service (chamber of agriculture) (2) French Vine and Wine Institute (IFV) (1)
Water and environment	Local public watershed body (1)	Local public watershed body (1) Administrative department committee (1)
Research	Researchers (4)	Researchers (4)

The simulation model developed during the course of the process is made up of four modules simulating the spatial and temporal dynamics of water (evapotranspiration, infiltration, run-off) and wine production at field level. These modules were temporally and spatially paired using the OpenFLUID platform (Fabre *et al.*, 2013), allowing simulations for 30-year periods to be carried out over the entire watershed. The impacts of climate change and adaptation strategies were assessed for the most pessimistic climate scenario (RCP 8.5), using data from the CNRM-ALADIN model and for three timescales: 1981–2010, 2031–2060 and 2071–2100.

The heterogeneous nature of regional climate change impacts

The impacts quantified by the model concern phenology, the risk of climate on harvested quantity and quality (frost, sunburn and high temperatures during berry ripening), irrigation water requirements, yields permitted by water availability, and production volume at watershed scale. The involvement of stakeholders in the modelling process allowed the spatial heterogeneity of the environment and cropping systems to be taken into account, with a distinction being made between eight production sectors (climate × soil × designation × practices). Simulations of the reference situation in RCP 8.5 reveal different impacts for each sector (Naulleau *et al.*, 2022a).

By 2100, the phenological advance is more pronounced in the north of the watershed, with maturity occurring three weeks earlier than currently and two weeks earlier than in the south. Vine budding also takes place earlier, albeit to a lesser extent (7 to 13 days). Earlier budding does not increase the risk of frost, however, as the date of last frost also falls earlier in the future climate. That said, the combined effects of the phenological advance and rising temperatures mean that by 2100 there will be an increased risk of damage caused by high temperatures (leaf and fruit sunburn) between flowering and veraison. Similarly, berry ripening conditions are changing rapidly: night-time temperatures are set to rise by 3.5°C and 6°C by 2050 and 2100, which could affect the ripening process. In the future climate scenario and in comparison to a simulation of the current situation, irrigation requirements will be 1.8 times greater by 2050 and 2.3 by the end of the century.

In the RCP 8.5 scenario, yields will fall by between 0% and 20% in 2050 depending on the sector, and by up to 30% in 2100 for the most productive sectors in the south of the watershed. These significant falls can be attributed to particularly low annual precipitation levels (below 530 mm/year on average). On a watershed scale, total grape production could drop by 10% by 2050, and by up to 14% by 2100, even with double the volume of irrigation water (figure II-6.5). The largest decline would be seen in non-irrigated PGI production. Situated in the north of the watershed, PDO production systems would suffer less of an impact, as they are already subject to water stress and have adapted to it.

Four adaptation strategies

Four adaptation strategies have been developed with stakeholders (Naulleau *et al.*, 2022b):

- Delaying harvests by using later grape varieties and promoting cooler microclimates in summer (hedges, row orientation, vine height)
- Limiting water stress by increasing the area irrigated and reducing the water requirements of vines (managing the leaf/fruit ratio, shading, mulching, reducing planting density, drought-tolerant grape varieties)
- Relocating vineyards in the watershed
- Enhancing the ability of vines to explore the available water capacity (addition of organic matter, soil decompaction, quality of scions and grafting techniques)

Each adaptation strategy equates to a combination of adaptation levers implemented in different sectors. Within the framework permitted by the numerical model, only the first three adaptation strategies could be simulated in part.

A strategy based on delaying the harvest through the use of late grape varieties was simulated. The simulation considered the introduction of such a variety (Cabernet Sauvignon type) throughout the watershed. It revealed only a slight effect on harvest dates (one week later compared to current grape varieties), and no significant impact on temperatures during berry ripening (+5.4°C instead of +6°C by 2100).

The strategy based on limiting water stress by means of water-saving practices was broken down into three substrategies, depending on the extent of the adaptations required. To begin with, stakeholders envisaged increasing the irrigated areas (irrigation strategy) by extending existing networks or building hill reservoirs. This strategy involved increasing irrigated areas across the watershed threefold, from 10% to 30%. Stakeholders also gave thought to implementing short-term adaptations (ST strategy), such as leaf area reduction and introducing grass cover in the southern sectors of the watershed. Finally, longer-term levers (LT strategy), such as reducing density and installing shade nets, were considered for PDO sectors in the north. These various strategies enable production losses across the watershed to be offset by 2050 only if strong measures are taken (density reduction, shade) and if irrigation is developed in areas where this is possible, by increasing the amount of water supplied by irrigation in the watershed four- or fivefold (figure II-6.5).

Finally, the planned extension of the winegrowing area involved replanting fields of vines where they had been located in the 1970s, mainly in the north of the watershed. This 20% increase in the area under vines would compensate for the drop in production at watershed level. However, this strategy makes the strong assumption that such extension is possible (accessibility of fields, cost, available workforce, etc.).

Stakeholder discussion of the results

Although the model's results were not called into question, stakeholders did make additional comments, particularly with regard to irrigation, taking the farm scale into account.

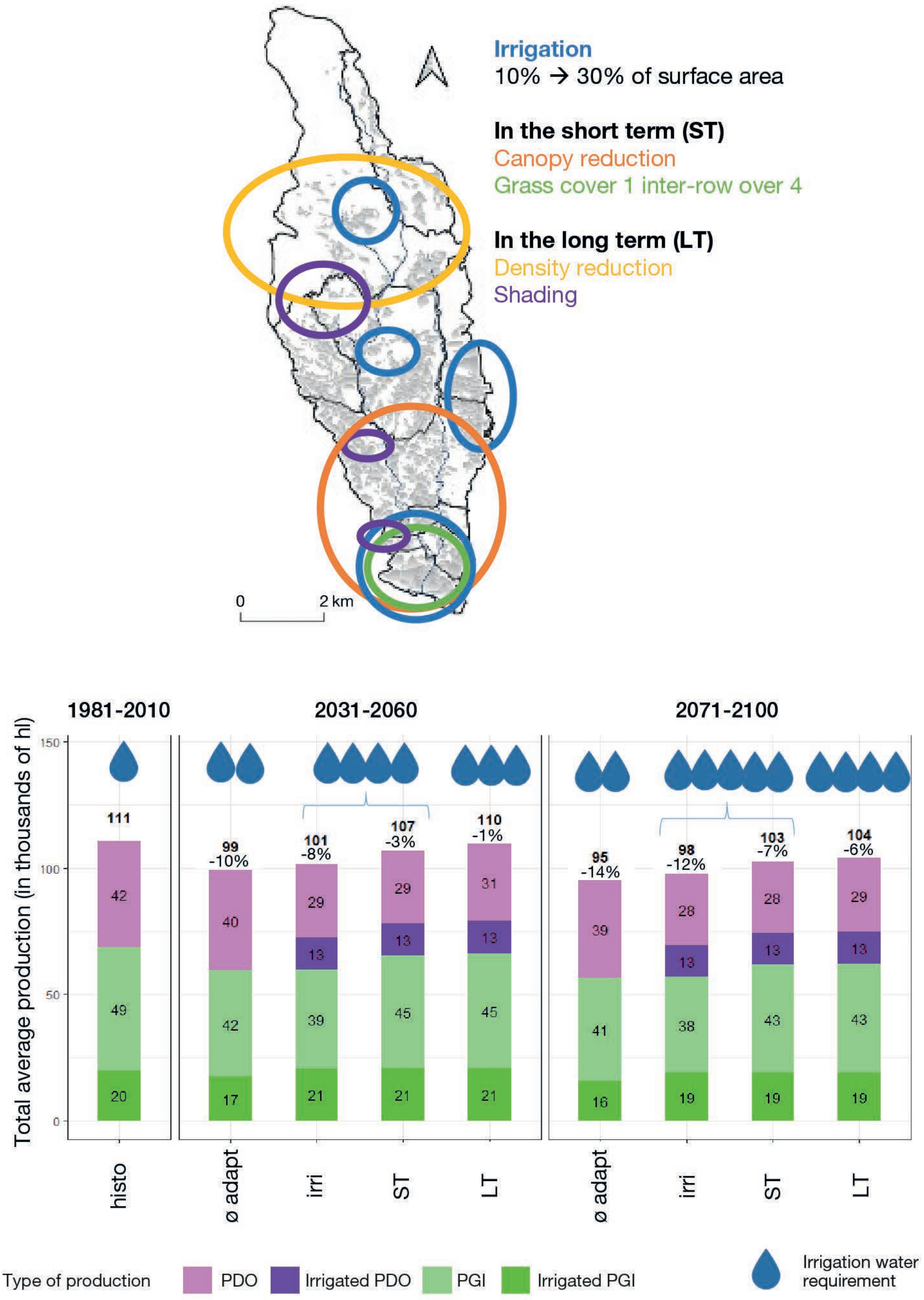

Figure II-6-5. Changes in total wine production and irrigation water requirements at watershed scale, in accordance with two temporal frames (RCP 8.5) and three adaptation strategies for limiting water stress. Irrigation: development of irrigation across 30% of the winegrowing area; ST: short-term adaptation (leaf reduction, grass cover); LT: long-term adaptation (density reduction, shading).

As regards irrigation, the results of the model indicate only a theoretical need for water in response to the production target, and not any real supply of water. Furthermore, the model assumes that water is always available for irrigation, which is not always the case with hill reservoirs, as pointed out by winegrowers in the local stakeholder group. Local stakeholders (winegrowers, representatives of the PDO association and the cooperative winery) thus stressed the importance of making irrigation objectives more explicit (vine survival, ensuring continued financial viability or increasing production) and controlling its use better (monitoring tools, regulation, prices). A representative of the IFV (a regional stakeholder group) also pointed out that the model was unable as yet to estimate the effect of irrigation in reducing vine mortality.

With regard to the farm's financial viability, local stakeholders (representatives of the PDO association and the local public watershed body) proposed a post-simulation analysis of the cost and benefit of each modelled lever by estimating costs incurred or avoided as a result of the new crop management and benefits linked to the increase in simulated yields. These cost-related estimates showed that all the adaptations proposed in the strategy for reducing water stress would be financially viable. These estimates also allowed us to look at new ways of adapting to the market and promoting the retail price of wine, as suggested in particular by local stakeholders, while questioning their ability to activate this "price" lever.

Some of the levers envisaged by the stakeholders could not be quantified by the model (drought-tolerant grape varieties, hedgerow planting, changing the grapevine management system, etc.). A qualitative assessment of the "desirability" and feasibility of these levers was nevertheless made during the final workshop. The exercise revealed that there was agreement between the two groups of stakeholders on certain results. For example, the levers deemed by the model to be the most effective in terms of production, such as shade nets or irrigation, were neither the most desirable nor the most feasible, owing to water resource availability, cost or aesthetics. The most desirable and feasible levers were improving soil quality and water-efficient management systems, which were not assessed by the model. Simulations quantifying the effects of the lever for improving soil quality and access to available water capacity would have been especially useful. However, they could not be modelled with the existing knowledge.

Adaptive grass-cover management, which was not simulated by the model, was also considered desirable and feasible by regional stakeholders but less so by local players. Local stakeholders rated canopy reduction, which was simulated, as the most desirable and feasible option, with regional stakeholders choosing to overlook it. In terms of planting material, drought-tolerant grape varieties were viewed as desirable by both groups of stakeholders, though they doubted there was an "ideal" grape variety that could fulfil PDO specifications, meet the challenges of climate change, and respond to the need to reduce the use of plant protection products.

Models for the participatory design of adaptation strategies: opportunities and limitations

The early involvement of stakeholders in the modelling process allowed models to be paired, an innovative step. Stakeholders steered the modeller's development choices towards processes they regarded as priorities. An in-depth assessment provided a more accurate estimate of wine yields in relation to the level of water stress. The combining of data from agricultural monitoring of fields in the watershed and trials conducted by technical and research institutes led to the development of the GraY model, a semi-empirical model for forecasting yield in relation to water constraints in the current and previous year (Naulleau *et al.*, 2022a).

A modelling process enhanced by local, expert knowledge

Joint strategies and simulations have the advantage of being locally relevant, depending on the local stakeholders, as they are based on proposals they consider relevant to their terroir and its development. It should be noted, however, that this may create a bias in terms of climate change, as these proposals depend on the defining and objectivization of the future situation, which is purely theoretical in nature. Although the information produced by projections has been discussed in detail, it is no easy task to foresee what a radically different climate future, beyond what we have already experienced, might hold. These strategies are innovative in nature, in that they go beyond the contents of PDO specifications. However, they remain conservative in their objective, which is to maintain wine production in the region. These are adaptation strategies, not transformation strategies (as per Folke *et al.*, 2010), and do not lead to the system being redesigned (as per Hill and MacRae, 1996) for the benefit of other crops, sectors or activities. This may have something to do with the types of participants, the vast majority of whom are wine industry stakeholders and wish to remain so. The development of more disruptive strategies would require involving a wider range of stakeholders in the process, or researchers themselves proposing more extreme strategies. However, the main obstacle to the simulation of bolder strategies was the limited number of levers that can be simulated by existing mechanistic models.

Local, expert knowledge enhanced by the modelling process

Participant evaluation of the process revealed that both groups expected to *see*, *know* and *understand* the effects of climate change and its adaptations – expectations that were met in part. The modelling process helped them prioritize the issues they face. We did not observe any change in action over the two years of the study, with the exception of one winegrower, who told us they had changed the row orientation of a new vineyard, following discussions during the initial workshops. However, local stakeholders, and in particular PDO winegrowers and representatives, say they are more aware of the levers available to them for adapting to climate change and are keen to innovate. Regional stakeholders said that the study reinforces existing dynamics for the provision of information on climate change and its adaptations, while expanding the potential range of levers and venturing beyond the framework for extending irrigation.

The study's principal strongpoint, as highlighted by both groups of stakeholders, is the *exchange* and *sharing* of information brought about by the modelling process at various stages. What climate can we expect in the future? What adaptations should the model consider? How can they be distributed spatially? What kind of performance can be expected? The jointly designed model has thus demonstrated its ability to simulate several contrasting production sectors, with differing climate change impacts (Naulleau *et al.*, 2022a). This proved important for both groups of stakeholders, as it enabled local stakeholders to anticipate different impacts depending on their location, as fields are often spread across several areas, and allowed regional stakeholders to identify contrasts between production scenarios representative of the Languedoc winegrowing area. Although the model was unable to simulate all the levers envisaged by stakeholders, it did provide information on the effect of different levers and their combinations, highlighting the ability of the models to explore wide ranges of variation. Finally, 30-year simulations revealed inter-annual variability, particularly in terms of irrigation requirements (Naulleau *et al.*, 2022b). This temporal variability is especially critical for winegrowers and cooperatives, given that a drastic drop in production could endanger their business. However, the main weakness of the approach is the limitations and uncertainties surrounding these models. The question is whether there is sufficient existing knowledge of mechanistic vine modelling for these models to be used in a participatory approach, and how gaps can be filled so that they can be used for the benefit of stakeholders.

Conclusion and outlook

To date, few studies on climate change adaptation have combined modelling and participation. That said, there are conceptual frameworks that do this (e.g. companion modelling; ComMod, 2005), just as there are preliminary approaches to integrating modelling into the implementation of participatory approaches with farmers. For example, the STICS mechanistic model (Brisson *et al.*, 2003) was used in the development of the Rami Fourrager serious game to simulate the performance of different combinations of forage crops and crop management (Martin *et al.*, 2012). The game was then used with livestock farmers to design forage systems adapted to climate change, generating stimulating discussion of potential changes (Martin *et al.*, 2012). However, these studies did not co-build models with stakeholders and focused on the farm level. Prior to this study, there was no framework for using mechanistic models on a watershed scale, as part of a participatory approach to meeting the challenges of climate change. This study points to two main challenges for the "stakeholder-oriented" use of mechanistic models: the "translation" of simulation outputs into information that can be understood and used by stakeholders; and the integration of different types of information sources as inputs to these models.

The "translation" of the model's raw outputs into evaluation indicators of interest to stakeholders is a key stage in the scenario evaluation process (Allain *et al.*, 2020). This step is all the more important in the context of climate change, where there are numerous model outputs (several scenarios, multiple time frames, etc.). Mutual understanding of the processes represented in the model, in relation to territorial issues in question, requires several modelling/participation loops, which are key to improving representations of model outputs. To some extent, our decision to analyse 30-year periods was compatible with the participatory approach, as participants were able to react to these projections and valued the specific climate information they were able to obtain. However, this decision had its limitations in terms of the collective ability to plan ahead and create specific strategies. In other studies, the participatory construction of adaptation scenarios has produced satisfactory results by focusing on just a few climate years (e.g. Sautier *et al.*, 2017) or by working on time frames that do not go beyond 2050 (e.g. Schaap *et al.*, 2013). Because grapevines are perennial plants, one option could be to consider consecutive years, probably with a shorter time-horizon.

A wide range of information was needed to represent winegrowing activities in the Rieutort watershed as input to the model: generic data from national databases (e.g. *Registre parcellaire graphique* – RPG, BDSol, INAO, Météo-France); quantitative data provided by local bodies (e.g. grape varieties, planting densities, production types); data from field measurements (e.g. water stress); qualitative information supplied in workshops (e.g. delimitation of soil types). Thanks to the hybridization of this information, a consensus was reached in representing the study watershed and continuing the process. However, this consensus is not entirely satisfactory to either soil specialists or winegrowers themselves, who are faced with greater heterogeneity in their vineyards than is represented in the model. While this does not call into question the results of the model, it may limit the ability of winegrowers to "recognize" themselves in these scenarios. Similarly, the model's representation of processes is based exclusively on scientific work. There are other, more collaborative data sources that could help guide the development and use of models with stakeholders. An example is the creation of a water stress observatory, which could be fed in part by data collected by local stakeholders voluntarily, using the ApexVigne application (Pichon *et al.*, 2021), for example. The information gathered would provide a better understanding of current variability in yield and quality in relation to practices and climate threats. Expert knowledge of processes that were not modelled, such as the tolerance of grape varieties to drought, could also be integrated in a more qualitative way (e.g. IPSIM model; Aubertot and Robin, 2013). Finally, the innovations currently being trialled by winegrowers ought to be studied (Salembier *et al.*, 2016) and made use of so they can be included in larger-scale simulations. Combining these three sources of information (participatory, expert and scientific) in the structure of a single modelling-based assessment tool would make modelling results more relevant to end users.

Chapter 7

PARTICIPATORY FORESIGHT APPROACH AND NATIONAL STRATEGY

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Introduction

Since 2003, French research has been geared to producing knowledge for the viticulture and wine industry so it can meet the climate challenge (Ollat *et al*., 2020). As part of the LACCAVE project, an original foresight-based exercise was carried out with several aims in mind. Its first aim was to contribute to the development of the project's interdisciplinary tools and to raise scientists' awareness of what an adaptive process represents, taking into account its drivers, levers and brakes, all with a view to building a shared vision of adaptation for the French viticulture and wine industry by 2050. The need to use these results as part of a participatory approach to raising awareness of the climate challenge among industry stakeholders then became clear. Ultimately, this approach has allowed the industry to draw up an adaptation strategy that will form the basis of an action plan (Aigrain *et al*., 2022). This whole approach is presented in this chapter.

The foresight approach used here is based on the SYSPAHMM method,[47] which involves developing possible future scenarios. Based on the principle that the future is not written and can be built, in part, by encouraging stakeholders and their organizations to act, this approach belongs to the science of anticipation, founded in France by Gaston Berger and in the United States by Herman Kahn (Godin, 2005). Unlike real "forecasts", these foresight-based scenarios – which are too distant or too complex to be probabilistic – must be coherent and plausible, but not formulaic, and must be sufficiently distinct from one another. Their relevance makes them a topic of interest to stakeholders, who can voice their reactions at participatory forums. (Ollat *et al*., 2021). They assist with long-term planning and anticipation. A recent report compiled by France's National Observatory on the Effects of Global Warming (ONERC, 2022) for the country's political leaders, which included a contribution from LACCAVE on the viticulture and wine industry, looks at the foresight-based approaches employed to envisage what climate change adaptation might look like in terms of state action.

In terms of the LACCAVE project, two approaches to climate change adaptation (innovating/relocating) were combined to propose four possible contrasting strategies.

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[47] The "Système processus, agrégats d'hypothèses micro- et macroscénarios" ("The micro- and macro-scenario process aggregation hypothesis system") was developed at INRA (M. and C. Sebillotte, 2002).

A relatively original "anticipatory retro-foresight" approach consisted of verifying that there was at least one pathway that would support the long-term development of each of these adaptation strategies. These pathways were developed by a steering group between 2014 and 2016 and drew on the results of research carried out as part of the project and hypotheses from previous foresight exercises in the industry (Sebillote, 2003; Aigrain *et al.*, 2016a). The four pathways and the adaptation strategies they support formed "scenarios" (FranceAgriMer, 2016) that were presented to industry stakeholders at seven regional participation forums (Ollat *et al.*, 2021). The objective of these forums was threefold: to compare the viewpoints of industry stakeholders; to encourage them to express their thoughts on the desirability or otherwise of these various scenarios; and to invite them to propose coherent action levers for achieving these objectives.

These aspects eventually formed the framework of a national strategy drawn up by the industry's professional leaders and presented to the Minister of Agriculture in August 2021. This chapter describes the various stages in the approach – without going into detail about the methodology – discusses the main impacts and contributions and concludes with a discussion of future prospects.

Using foresight principles to develop an "interdisciplinary" approach

The LACCAVE project created a network of 22 laboratories affiliated with INRAE, France's National Centre for Scientific Research (CNRS), and the universities and *grandes écoles*, and covered an array of scientific disciplines – from climatology and genetics to social sciences, physiology, agronomy, oenology and plant pathology. From the outset, it sought to propose a systemic vision of climate change adaptation so that the issue could be considered "at different spatial and temporal scales" and by combining technical levers with the choice of vineyard location, industry organization, the promotion of wine, and the regulations governing the industry (Ollat *et al.*, 2020). With this in mind, the drafting of possible future scenarios for the viticulture and wine system in the context of climate change helped to drive an interdisciplinary and collective approach and contribute to the LACCAVE project.

The creation of shared presentations

This foresight exercise was overseen by a steering group made up of foresight experts and industry specialists from Montpellier SupAgro, INRAE, FranceAgriMer and INAO, who worked alongside LACCAVE researchers. The leaders of each of the project's theme-based working groups (TWGs) were asked to present the major issues in their areas of expertise and to assign one or two researchers from their TWG to assist the steering group with its work.

This phase quickly led to the creation of a joint interdisciplinary presentation of the system and the identification of hypotheses that could aid the development of scenarios in the phases set out below (figure II-7-1).

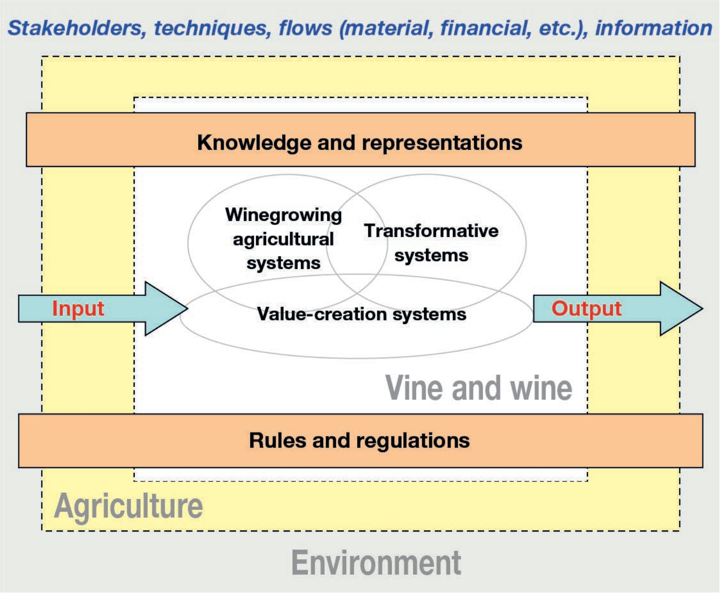

Figure II-7-1. A simple, generic presentation of the viticulture and wine system.

Predefining adaptation strategies

After proposing a systemic presentation of the viticulture and wine industry and choosing a median IPCC climate scenario in 2050 (+2°C), the method took a unique approach by predefining four possible adaptation strategies based on the adaptation levers identified in the research work. In terms of viticulture and wine, forms of climate change adaptation can be seen as the result of technical innovations, vineyard relocation, and institutional and organizational change.

Technical innovations include the choice of grape variety and rootstock (Duchêne *et al.*, 2010), new vine management methods (Van Leeuwen *et al.*, 2019), precision irrigation (Ojeda *et al.*, 2017), and oenological practices (Dequin *et al.*, 2017).

Vineyards can be relocated in the same terroir, making the most of its heterogeneous soil and climate conditions (de Rességuier *et al.*, 2020) or on a wider geographical scale, even in regions not known for winegrowing (Zavlyanova *et al.*, 2023).

Institutional and organizational changes are linked in particular to geographical indications (PDOs and PGIs), which cover 93% of French winegrowing areas – with the INAO overseeing the demarcation of production areas – and the speed with which technical innovations and regulatory changes are incorporated into specifications. Institutional and regulatory changes thus provide a robust location and technical innovation framework and can be seen as conditions for their implementation. In predefining adaptation strategies, the steering group chose to focus on relocation and innovation, two areas that are, at first glance, less dependent on one another (Aigrain *et al.*, 2016c):

- The extent to which vineyards are relocated can thus vary. They can remain strictly within the boundaries of their current location, relocate within or on the edge of a production area, or move to create an entirely new winegrowing area.

This mobility allows for "more favourable" climate conditions to be found elsewhere (depending on altitude, latitude, soil types, etc.).

- The scale of technological innovation (in winemaking or oenology) can vary, from its continuation to breakthroughs such as biotechnologies, GMOs, crop association and agrivoltaism. Innovations can change the way the viticulture and wine system works, mitigating impacts or even allowing it to benefit from climate change.

In combining these two areas, we can propose four adaptation strategies (figure II-7-2):

- "Conservative", which involves only marginal changes to existing vineyards
- "Innovate to maintain", which opens vineyards up to a wide range of technical innovations that ensure they stay put
- "Nomadic vineyards", which prioritizes their relocation in accordance with new climate conditions
- "All options open", which allows situations in which anything is possible anywhere to be trialled

"Zero adaptation", which would not lead to changes in practices or locations, was ruled out. A fixed system involving no reaction to climate changes whatsoever was viewed as too simplistic and not in keeping with the history of winegrowing, which has always had to adapt in one way or another.

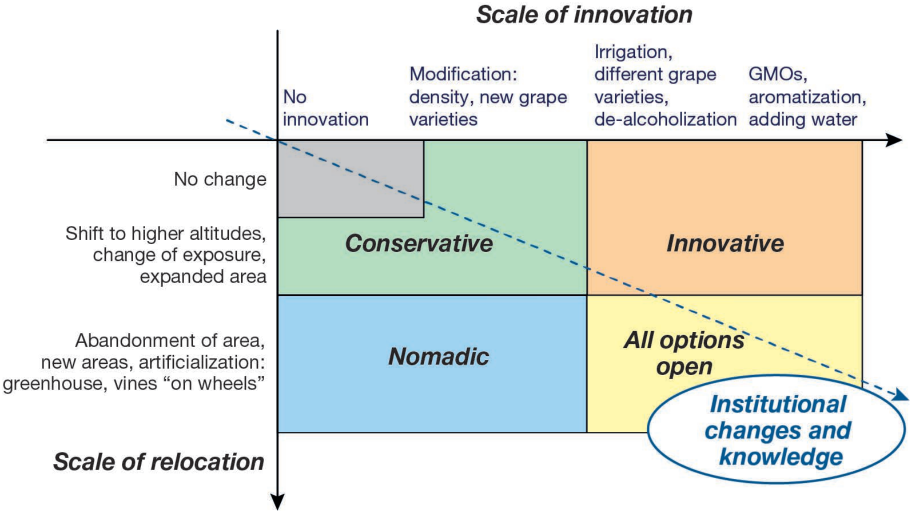

Figure II-7-2. Four predefined adaptation strategies. Source: FranceAgriMer, 2016.

Sources of hypotheses

A corpus of hypotheses, expressed in simple sentences in positive and negative form, was created to construct pathways supporting the development of each strategy. This corpus was based on the following:

- The work of researchers in the LACCAVE project, covering a wide range of scientific fields and disciplines. An example of a positive hypothesis reads, "New oenological practices preserving wine characteristics are being developed", while the negative form says, "There are no oenological innovations that allow wine characteristics to be preserved".

- Interviews with industry professionals from a number of winegrowing regions (Juan, 2014). An example of a positive hypothesis reads, "Despite the pressure exerted by climate change, the pace at which innovation is embraced and changes made in practices in PDOs remains slow, with actions being taken on a collective level", and the negative form says, "Climate change is leading to an acceleration in the pace at which innovation is embraced in PDOs, with individual trials an option".

Climate change is not the only factor affecting the viticulture and wine system, however. The various other forces exerting pressure include growing concern (on the part of society and the World Health Organization) about the health effects of alcohol, the spread or otherwise of world trade to new countries, changes to the European Union's common agricultural policy, and the acceptance of GMOs by consumers and producers. Contextual hypotheses from previous foresight studies on the viticulture and wine industry have been added to the corpus of specific hypotheses. For example, a positive hypothesis reads, "In Europe, agricultural land is subject to extensive planning, with the most fertile land reserved for food crops, while vines are confined to areas where the soil is less fertile", and the negative hypothesis, "In Europe, agricultural land is not subject to extensive planning, with vines being planted on the most fertile land". This work led to the identification and selection of 70 hypotheses. The links (relationships of influence/dependence) between them were researched, generating hypothesis aggregation and allowing the four pathways preferably leading to the four possible predefined adaptation strategies to be drafted (Aigrain *et al.*, 2016a).

Pathways to possible predefined adaptation strategies

These four pathways can be summarized, in very general terms, as follows.

Conservative strategy pathway

Against a backdrop of pressure from health authorities on alcoholic beverages and land and water management prioritizing food crops, the industry, which has few links to research, sees climate change as a threat. Given the importance of wine in French culture and its place in the landscape, which makes it much more than an alcoholic beverage, geographical indications[48] (GIs) and the regions that produce them are islands of resistance in a shrinking wine industry.

Innovative strategy pathway

Environmental and health issues are driving change, with viticulture and winemaking embracing a growing number of innovations. This development comes at a time when circumstances favour a degree of stability in French winegrowing regions and when EU policy is restrictive in terms of agricultural zoning yet relatively liberal with regard to actual winemaking.

Nomadic strategy pathway

In a context shaped by restrictive alcohol policy and research focused on reducing inputs, consumers, in their desire to rediscover the source of their wines, are encouraging the

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[48] Geographical indications include protected designations of origin (PDOs) and protected geographical indications (PGIs).

viticulture and wine industry – which lacks the knowledge needed to maintain, even in a loose sense, the consistent quality that is hoped for – to take the reputation of the great designations elsewhere and establish vineyards where water resources are plentiful (mainly in the plains).

All-options-open strategy pathway

In a more open and largely favourable context for the wine market, the choices made by new investors in terms of production and, in particular, trade lead to a relocation to irrigated centres, some old terroirs and new vineyards benefiting from climate change. Customized wines and regional brands remain on the market, but most of what is on offer is made up of technological wines controlled by a few downstream producers. Climate instability, competition between winegrowing areas, deregulation and domination by a few firms are ultimately undermining disorganized winegrowers, which are unable to benefit fully from R&D activities.

The full versions of these pathway presentations can be found in FranceAgriMer (2016) and Aigrain *et al.* (2016b) (available in French only).

Regional forums discussing foresight and generating proposals for action

Over the last 10 years, foresight experts at FranceAgriMer and Montpellier SupAgro, who headed up this initiative, have developed participatory feedback practices from foresight exercises carried out with various agricultural sectors, including viticulture and wine. Given the interest in and feasibility of this kind of exercise, INRAE centres and wine trade associations in winegrowing regions were asked to bring together industry stakeholders concerned by climate change and willing to contribute to proposals for action.

The first aim was to inform industry professionals about the work undertaken as part of the LACCAVE project, and to present climate change, its observable impacts and ongoing research into adaptation. The main objectives were to share the four imagined scenarios, then provide a record of the range of viewpoints and positions, and finally reflect together on what room for manoeuvre there was in anticipating the possible futures described.

The organization of participatory forums in seven winegrowing regions

The four adaptation strategies and the pathways leading to them were presented and discussed at seven participatory forums attended by more than 500 professional viticulture and wine stakeholders and held between November 2016 and March 2019. These forums took place in France's main winegrowing regions: Alsace; Bordeaux-Charentes and South West; Burgundy and Beaujolais; Champagne; Languedoc-Roussillon; Rhône Valley and Provence; and Loire Valley). Participants hailed from production; R&D and consultancy; and administration, trading and other activities. Each of these three groups accounted for around a third of participants.

The same method was used in each region and involved four stages:

1. Presentation by the organizers of the context and adaptation scenarios;
2. Participants were divided into groups to discuss the issues and consequences of each adaptation pathway;
3. An individual vote on each of the adaptation scenarios, with participants choosing from five possible strategic stances: positive proactivity (act now to promote the scenario), negative proactivity (act now to prevent the scenario), anticipatory reactivity (to prepare for the scenario), watchfulness (to monitor and look ahead), and indifference (this scenario is of no interest);
4. Proposed actions to be implemented to promote or prevent these different adaptation scenarios.

Innovate to maintain: the preferred option for stakeholders

The results of the votes (table II-7-1) on the various adaptation scenarios were similar across the seven regions, although there were some specific regional variations, depending on climate and socioeconomic characteristics (Aigrain *et al.*, 2019; Ollat *et al.*, 2020). For example, stakeholders in the Loire Valley were less inclined to reject the "conservative" scenario and were keen to anticipate its possible resilience capability in an area where climate change is seen as "a little less restrictive than in other regions" (Touzard *et al.*, 2020).

Table II-7-1. Strategic attitudes chosen by participants for each scenario, as a percentage of the votes cast by participants in the seven forums. Source: Touzard *et al.* (2020).

Scenarios	Conservative	Innovative	Nomadic	All options open
Positive proactivity	21%	73%	3%	5%
Negative proactivity	30%	3%	39%	59%
Anticipatory reactivity	30%	22%	29%	16%
Watchfulness	16%	1%	27%	18%
Indifference	3%	1%	2%	2%

Like its regional counterparts, the national summary shows that the majority view is to adopt the innovative scenario. What are its limitations, however? "Innovate at all costs" or "innovate to maintain"? This scenario can be seen as a way of maintaining organized winegrowing linked to the terroirs. "Innovate to maintain" means preserving the individual and collective investments made in the area (heritage, image, other activities, social links, etc.), all of which combine to create the value of wine.

The conservative scenario attracted the most mixed vote. This reflects varying perceptions of the resilience of existing winegrowing areas, depending on the region (some are more or less impacted and competitive than others, with Alsace and Champagne being the most in favour), the category of stakeholder (winegrowers the most in favour), and the level of satisfaction with the current state of affairs.

The rejection of the nomadic scenario is motivated by the fear of change in the conditions in which winegrowing areas compete and the removal of historic terroirs and landscapes, even if the typicity of wines would be maintained by relocation. Aside from rejection, this scenario raises the following question: Can new winegrowing areas really develop elsewhere? and should they be "monitored"?

The all-options-open scenario was more convincingly rejected. It is generally seen as a threat with the potential to disrupt points of reference and cause winegrowers to lose influence, particularly in the value chain, linked as it is to the importance of geographical indication production in France.

Proposals for action to promote or prevent scenarios

Finally, each stakeholder was asked to suggest actions that would promote or prevent these scenarios, or to prepare for them. A total of 2,700 proposals for action were collected and then organized into four main areas: research and trials; regulatory changes; support for local solutions; and training and communication.

Analysis of them reveals that there is no "one-size-fits-all" solution (e.g. "all grape varieties" or "all irrigation") in terms of technical innovations, changes to institutions and bodies, and individual and collective actions. There is a strong emphasis on the predominant roles of R&D and information to be given out to industry stakeholders. Variable options potentially embracing different winegrowing models and even coexisting with each other were highlighted: for example, highly technological PGI winegrowing that benefits greatly from irrigation; and innovative, regional and local PDO winegrowing, with significant development of agroecology and organic farming. There are variations from region to region, due to the differing impacts of climate change, product orientation and regional organization. Links were established with other issues, including the environment and societal expectations. Some questions were barely touched on by participants, such as links with consumers, measures to reduce greenhouse gas emissions, and risk management.

From the joint development of a national strategy to action in winegrowing regions

At the same time as these forums were being held, the foresight steering group organized a handover to national industry leaders. As well as information going out in industry networks and the media, two key presentations of the foresight approach were given at the World Vine and Wine Congress[49] (Aigrain *et al.*, 2016a et b). French industry leaders present at this event expressed a keen interest and took part in an exploratory meeting with the leaders of the foresight project.

Passing the baton to industry organizations and helping them to build a consensus

A national working group was set up under the aegis of FranceAgriMer and the INAO. It met six times between December 2016 and late 2018 to review work, train and inform the industry's main organizations, and help prioritize the 2,700 regional-forum proposals, according to their urgency and importance.

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[49] The OIV is an international organization for the viticulture and wine industry. It is an intergovernmental scientific and technical body with recognized competence in the field of viticulture, wine, wine-based drinks, table grapes, dried grapes and other vine products.

Representatives of the country's major wine organizations set up a "political steering group", which set out the objectives of a national strategy at its last meeting in late 2018: "To promote the emergence of the innovative scenario; develop actions to prevent the nomadic and all-options-open scenarios; take into account the range of votes on the conservative scenario; use all available levers for the following: regulatory aspects, communication and marketing, collective actions, R&D, and transfer to wineries". These objectives were validated by the industry's representative bodies (the INAO's national PDO and PGI committees and FranceAgriMer's wine board). The strategy was developed to ensure a sense of consistency between national and regional expectations and considerations, which had come to light during the course of the LACCAVE project and its foresight exercise in particular. The strategy should allow the industry to be more responsive and effective in a collective sense, and also provide a well-planned framework that supports the various requests for change on a technical, socioeconomic and regulatory level. It also sought to inform the OIV, the European Commission and the other member states about the French strategy, the idea being to aid their understanding of the approach and smooth the way for the development of regulations in the future common agricultural policy. It should also lead to a greater emphasis on the wine industry in the National Climate Change Adaptation Plan currently being drawn up by the Ministry of Agriculture (Hannin *et al.*, 2021; Aigrain *et al.*, 2022).

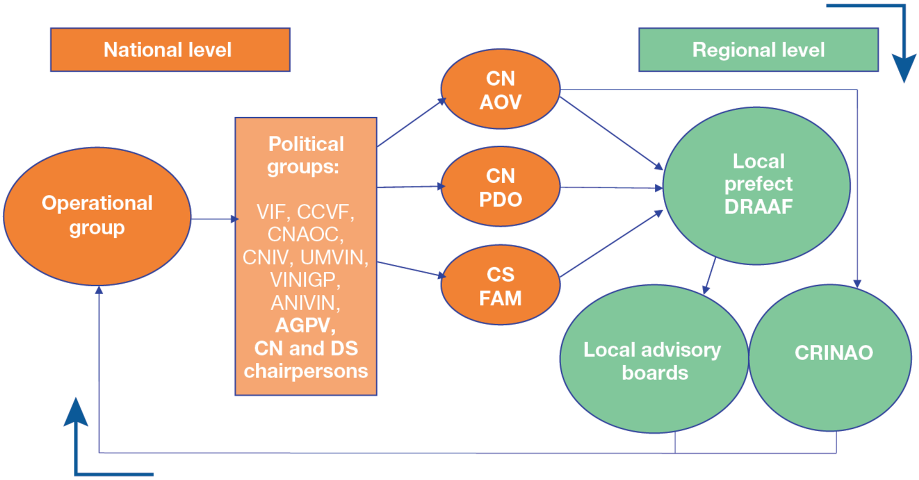

Figure II-7.3 Proposed governance of the climate strategy for the viticulture and wine industry. Source: Aigrain *et al.* (2022).

VIF: Independent Winegrowers of France; **CCVF**: Cooperative Winegrowers of France; **CNAOC**: National Confederation of Winegrowing PDOs; **CNIV**: National Wine Trade Committee for Designation of Origin and Geographical Indication Wines; **UMVIN**: Union of Wine Houses and Brands; **VINIGP**: Confederation of French PGI Wines; **ANIVIN**: National Association of French Wine Trade Organizations; **AGPV**: Wine Production Association; **CNAOV**: National Committee of Protected Designations of Origin; **CNIGP**: National Committee of Protected Geographical Indications; **CSFAM**: FranceAgriMer Wine Board; **DRAAF**: Regional Department of Agriculture, Agrifood and Forestry; **CRINAO**: Regional Committee of the French National Institute of Quality and Origin.

A draft national strategy was drawn up in 2018 and 2019 by the policy group, with the support of the operational group, and summarized proposals put together and structured around eight priority themes for action. The project was presented to regional representative bodies (regional winegrowing boards and INAO regional committees) at the end of 2019 (figure II-7.3). The aim was to gauge their reactions and identify other actions that had been planned or already implemented in the region. This mechanism, which combines a top-down (national guidelines) and bottom-up approach (feedback from the regions), allowed regional winegrowing organizations to become more involved on an official footing. It also enabled existing and planned regional initiatives to be taken into account and regional adaptations to be incorporated, as a priority, into the draft national strategy, particularly in view of geographical variations of climate change.

Feedback from this consultation was analysed by LACCAVE researchers, who compared it with the research work being carried out at different laboratories. The feedback was also included in the final strategy document submitted to the Minister of Agriculture by the industry's national representatives on 26 August 2021.[50]

From action plan to action: time for industry professionals to take over

Ultimately, the national strategy proposed by the industry was based on seven areas: improving knowledge of winegrowing areas; taking action on production conditions; promoting suitable varieties and rootstocks; taking action on oenological practices; developing markets and guaranteeing production; promoting research, development, knowledge transfer and training; and helping to mitigate climate change. Some 40 priority actions were identified for these areas.

This strategy was translated into an action plan as part of an agreement signed in 2022 by the French winegrowing industry's main management and representative bodies: FranceAgriMer's Wine and Cider Board, the INAO's national PDO and PGI committees, CNIV, INRAE, IFV, the French Ministry of Agriculture, ANIVIN, UMVIN, Coop de France, APCA, Independent Winegrowers, the Confederation of PGI Wines, and Régions de France, among others. The IFV headed up the various working groups set up for this purpose (steering committee, monitoring committee and technical committee).

The aim was to compile an inventory of operational research results and to be in a position to summarize them for winegrowing areas in "solution packages", each comprising a range of innovations for creating robust "regional models". An R&D plan was drawn up to oversee and fund a large number of regional trials in adaptation-related issues, taking place in "regional demonstrators". Employed for trialling innovations, they bring producers together and organize the transfer of practical solutions for adapting to and mitigating climate change to all regional stakeholders in the viticulture and wine industry. Based on a global approach and involving upstream industry (PDO and PGI product protection and management bodies) and wine trade organizations, this approach includes four types of action:

- Inventory and evaluation of solutions
- Setting-up of regional demonstrators and creation of a national network of innovative sites
- Coordination of the network and consolidation of practices
- Project coordination and communication

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[50] National strategy document available at: https://laccave.hub.inrae.fr/prospective.

In terms of training and research, the IFV was tasked with putting together a national R&D project that combines climate change adaptation and mitigation and takes the expectations of winegrowing regions into account.

This approach also led to a proposal to amend irrigation regulations (new Decree no. 2023-735 dated 08/08/2023, see chapter I-7) and to the development by the INAO of a system for adaptation testing of new varieties for PDO and PGI wines. The aim is for this national drive to be coordinated at regional level through wine trade associations and non-PDO organization, for the benefit of the entire industry.

Conclusion

Conducted by a group of experts from INRAE, Montpellier SupAgro, universities, the INAO and FranceAgriMer, all as part of the LACCAVE project, the foresight study began by drawing up four possible predefined adaptation strategies. This was followed by the creation of four pathways for each of them, with a set of guiding hypotheses on the development of the viticulture and wine system. The scenarios were submitted to 500 industry stakeholders in seven winegrowing regions, for their analysis and agreement on the preferred strategic approach to each of them, namely prepare, promote or prevent. In compiling a database of the strategy-related attitudes of forum participants and their proposals for action, the group of experts provided national industry leaders with broad guidelines and a methodology for creating a national adaptation strategy. Presented to the Minister of Agriculture in August 2021, the strategy is currently being turned into an action plan, with the aim of linking national and regional approaches. The whole process has taken around eight years.

The initial approach to developing interdisciplinary tools in a research project was ambitious in itself. On a scientific level, it provided a platform for interdisciplinary dialogue between researchers and led to a more systemic approach to resolving issues. Furthermore, the scenario-building method, based on clearly contrasting predefined strategies, proved to be effective when it came to perceiving possible futures for agriculture within the context of climate change. It also produced very specific and applicable results that have energized the industry and spurred it into action.

The use of foresight by the French viticulture and wine industry to develop its strategy has had an impact both domestically and around the world. The work was presented at the World Congress of Vine and Wine in Punta del Este, Uruguay (Aigrain *et al.*, 2019), to the Copa-Cogeca Wine Group in May 2019, and at a number of international conferences. In France, other industries have adopted this approach to climate change adaptation: Forestry and woodland, at the request of the National Center for Private Forest Ownership (CNPF); arable crops at the request of FranceAgriMer's specialist board. The part of the dairy industry covered by geographical indication labels also expressed an interest. Focused on pesticide-free viticulture, PPR VITAE is another large-scale scientific project to implement a similar foresight-based approach and is drawing on lessons learned from the successful LACCAVE project.

Nevertheless, the slowness of the whole process – from the creation of interdisciplinary links between scientists in 2012 and the debate on scenarios from 2016, to the official submission of the action plan to the Minister for Agriculture in 2021, which is merely the start of solution implementation – shows that climate change adaptation, like any change dynamic, has to negotiate socio-technical and political obstacles, not to mention the interplay of stakeholders influencing the process. An illustration of this is the sheer range of strategic attitudes expressed during the feedback phase of the foresight exercise on the conservative scenario and, to a lesser extent, the nomadic scenario. Such is the structure of the industry, which is largely founded on geographical indications and the value of the vines and the wines made from them, that every decision is both an individual and a collective issue. Yet in opening up areas for debate, presenting a range of possible futures that demand action, and highlighting room for manoeuvre and the possibilities for action, we may have helped stem growing environmental anxiety among viticulture and wine industry stakeholders and opened up avenues for collective action.

Final conclusion

Nathalie Ollat and Jean-Marc Touzard

In exploring the new field of research that revolves around vine, wine and climate change, this book gathers the contributions of researchers and their partners, who for the last 10 years have engaged in a productive and enthusiastic scientific partnership through the LACCAVE and LACCAVE 2.21 projects, supported by INRAE. The 16 chapters of this book present the project results along with updated summaries to help readers better understand the climate impact on grapevines and wines, assess adaptation levers, and co-create strategies at different scales, from winegrowing estates to national policy. This book provides new knowledge from a range of disciplines to strengthen the adaptation capabilities of wine industry stakeholders. This desire to participate in the adaptation processes themselves led LACCAVE participants and book contributors to come up with a series of key messages calling for adaptive co-management of winegrowing areas, and to pursue a new, cross-disciplinary and transformational approach to research.

The co-creation of key messages for industry stakeholders

At the closing seminar of the LACCAVE 2.21 project held 24–26 November 2021, researchers and their partners came together to produce a series of messages for the vine and wine industry, political leaders, and society in general. Drawing on theme-based summaries, preliminary messages were put forward, improved upon and selected at workshops before being put to winegrowers at the SITEVI trade show,[51] which followed the seminar. This original and participatory approach to message creation led to the drafting of a press release, which was covered by a number of media outlets.[52] Three years on, these messages remain relevant and topical, which has everything to do with the increasingly marked effects of climate change on the industry.

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[51] International trade show for vine and wine producers.

[52] In particular, an article published in *Le Monde* on 16 December 2021 and entitled "*Climat : les pistes du projet Laccave pour sauver les vignes*" (Climate: LACCAVE project plotting a path to vine salvation). There was also coverage by *Le Paysan du Midi*, *Vitisphère*, and, at a later stage, France Inter, the *Financial Times*, and CBS, among others.

The first message is a serious warning. It is worth reiterating that the impact of climate change is only intensifying in winegrowing areas. It is disrupting the way vines and their ecosystems function and has knock-on effects on wine characteristics, the development of industries and markets, the geography of winegrowing areas, and the risks and viability of many businesses.

However, adaptation solutions are possible if the rise in average temperature is restricted to around 2°C and if industry, the authorities and the research world continue to work together. There are many adaptation levers and they need to be trialled at a faster pace. With this in mind, participants in the LACCAVE project selected eight other messages targeting these levers:

1. The conservation and improvement of winegrowing soils must be given priority if we are to promote the resilience of vineyards by monitoring grass cover, adding organic matter (compost, mulch, conservation grazing, etc.), taking anti-erosion measures, etc.
2. Renewing and diversifying planting material is also a key option as it would enable the planting of later-ripening grape variety/rootstock combinations that are resistant to drought and higher temperatures and produce less sugar or more acids. This option encompasses ancient varieties, those grown in other regions, and new varieties. To bring this about and encourage the sharing of information, support must be given to collections and conservatories, individual and collective experiments and observation networks, all of which must also be coordinated.
3. Water should be managed in a systemic way and on a regional scale and take into account wine types, grape varieties, winegrowing practices and soil management, which regulates the circulation of water and its recharge from autumn and winter precipitation. Precision irrigation can be used to control vine water status, but its generalized use is neither possible nor desirable. Water-efficient and agroecological farming practices should be promoted, as should good crop management so that most vineyards can remain rainfed.
4. While there are methods for adapting winemaking to limit the effects of climate change (by reducing alcohol content or adjusting acidity, for example), systemic and applied oenological research into new varieties is still required.
5. Spatial heterogeneity across a small winegrowing region is a resource for adaptation, which involves new knowledge, mapping and modelling. Local management of fires, ecosystems and landscapes requires a winegrowing governance structure that includes other local stakeholders. Climate change thus requires new approaches to landscape engineering in winegrowing regions.
6. Climate risks are disrupting economic strategies. Private insurance schemes must be applied along with public and joint support schemes and investments, prevention measures, improved information and warning systems, and new options for wine reserve management and market diversification.
7. Taking consumers into account is essential to understanding their preferences as wines and adaptation innovations evolve, and also to raising their awareness and involving them in strategies designed to tackle climate change.
8. The wine industry must contribute to climate change mitigation by reducing its emissions and capturing carbon. There are many avenues for doing so, such as soil and landscape management, logistics, and building insulation. Such engagement will not go unnoticed by consumers, thus enhancing the image of wine.

One final, all-encompassing message is that the LACCAVE project highlighted the need to design and evaluate combinations of these various adaptation levers, using systemic and participatory approaches to build strategies at different scales of action: vineyards, catchment areas, winegrowing regions and the domestic wine industry, where the adaptation strategy developed as a result of this project is implemented.

Adaptive co-management of winegrowing areas at multiple scales

"Creating and coordinating adaptation strategies at different scales" gradually became a major research issue in the LACCAVE and LACCAVE 2.21 projects, as the chapters in the second part of this book showed. Yet over and above the desire to produce scientific knowledge that can spur action, the project participants helped put together a new management perspective for the vine and wine industry, one that involves moving towards adaptive co-management of winegrowing areas, regions and the wines they produce. This proposal takes up the results of research into the management of social and ecological systems in response to climate change (Plummer, 2013; IPCC, 2022). It is also the pragmatic outcome of LACCAVE's foresight studies, the results of which were enhanced by participatory forums in seven winegrowing regions, and then harnessed to co-create the national adaptation strategy (chapter II-7).

Adaptive co-management gradually emerged as an approach in exploring different adaptation pathways, and in highlighting the issues and outcomes involved. Doing nothing and relying solely on nature and tradition is not an option, as it would mean suffering the ever-increasing impact of climate change. Nor does relying on changes to practices and grape varieties within the framework of the industry's existing rules seem sufficient in the face of the quickening pace of climate change. That said, the widespread relocation of vineyards with a view to finding favourable climate conditions elsewhere would appear to be impossible on a political and societal level and entail a whole host of unknowns. Liberal regulation, based on the promises of the market and technological innovations, would totally disrupt the industry and has been roundly rejected by stakeholders (Touzard *et al.*, 2020). On the other hand, speeding up innovation to allow winegrowing to stay in its existing terroirs is a popular option in all regions, albeit with an awareness that the excessive artificialization of systems could potentially sever the links between wine and its local region. This is where adaptive co-management comes in, by mapping out this latter adaptation pathway.

Adaptive co-management of a vineyard and its region and wines can be seen as an iterative (or circular) process of exploring, implementing, monitoring/evaluating and rethinking solutions (planting material, technical and oenological practices, management of local resources, communication and organizational actions in the industry, etc.) to develop sustainable winegrowing that is able to withstand climate change (Boyer and Touzard, 2021). At local and regional level, it is founded on a collective approach, which may be led by a protected designation management body, for example, and open to consumers and stakeholders involved in managing local resources necessary for adaptation, such as soil, ecosystem, landscape and water. This process is backed up by a dynamic of continuous experimentation and learning, designed to make winegrowing systems more resilient. Its development is linked to a series of conditions and actions, many of them already envisaged or implemented:

- Updating PDO or PGI principles, which may continue to safeguard a specific quality linked to a region, but which may evolve and which must express, above all, a guarantee of adaptive (and sustainable) co-management of the region's resources;
- More flexible specifications, including more practices linked to the environment and climate change mitigation, a direction that the INAO has already taken with the option of introducing varieties of interest for adaptation and testing innovations;
- The development of training courses for winegrowers and industry stakeholders, and of "new terroir engineering", combining skills in diagnosis, spatial analysis, climate simulation, experimentation, and the adaptive and participatory management of local resources;
- Changes in public policy, recognizing the contributions of agriculture and winegrowing, and supporting innovations and approaches associated with the adaptive co-management of winegrowing areas.

Cross-disciplinary, transformational and media-friendly research

The adaptive co-management of winegrowing areas also hinges on researcher involvement, and calls for a new era of partnership and participatory research into grapevines and wine. This "new" way of doing research was tested pragmatically in the LACCAVE project and provides a thread common to every chapter in this book. The desire to study and support climate change adaptation processes in the industry led researchers to embark on a new way of producing scientific knowledge that is cross-disciplinary, transformational and media-friendly.

The complexity of the impacts of climate change, the many aspects and dimensions of the analysis of adaptation solutions, and their combination at different spatial and temporal scales in the design of strategies have prompted researchers from different disciplines and laboratories to work together on vine and wine, and produce interdisciplinary and systemic knowledge. Growing demands from stakeholders in a well-organized industry that is increasingly concerned by the quickening pace of climate change have also led researchers to involve these stakeholders in their projects and to engage with them in reflection, discussion and actions aimed at transforming winegrowing activities and how they are managed at the regional and sectoral level. In addition to these participatory initiatives with industry stakeholders, wine's special place in French society also led researchers to produce documents and videos for a wider audience, and to take part in a number of media initiatives. In the process, viticulture and wine have become a means of raising public awareness of climate impacts and the challenges of mitigation and adaptation. Although the issue of mitigation was not covered in the LACCAVE project, and is given little consideration in this book, researchers and their partners affirmed the importance of combining it with adaptation. To give ourselves continued room for manoeuvre in terms of adaptation, we need to do everything we can to keep global warming below a 2°C temperature rise, a level that seems compatible with the adaptive co-management of "terroir-based viticulture".

Supporting just such an outcome are new INRAE guidelines promoting participatory science and research and the backing provided over 10 years by its ACCAF meta-programme. It has also been influenced by general sociopolitical changes, which have expressed the urgent need for climate action (COP21 in Paris) and looked to scientists to come up with new policies, although the measures implemented to date are still too limited. That said, the initiatives, commitments and collective actions instigated by researchers in projects such as LACCAVE have all been meaningful.

This book describes an adaptation pathway embarked on by researchers and their partners and leading to changes in their activities, professions and contributions. These changes include producing scientific knowledge on processes (impact and adaptation) based on observations and modelling; providing expertise based on this knowledge; developing new participatory methods; raising the alarm on key issues; becoming communicators and debaters; co-creating solutions and supporting public policies; and opening up areas of social experimentation for the transformation of winegrowing systems.

This pathway transformational science (Fedele *et al.*, 2019) is but one step, however, in developing knowledge for climate change adaptation. The fact is that the contributions in this book raise a whole host of questions. It goes without saying that we need to continue our work on climate impacts, particularly at the grapevine and terroir level, and on the many interlinked effects in viticulture ecosystems and landscapes. The exploration and analysis of solutions must be extended to new areas and options encompassing, for example, agroecological, digital, biotechnological and robotic innovations. Though risk management and awareness of extreme events is an issue that has yet to be addressed in any great depth in winegrowing, it is becoming crucial. The evaluation of solutions (multicriteria, environmental, economic) and their combination in adaptation pathways in particular remains a key area of work. In more general terms, the conditions for developing adaptive co-management of winegrowing areas and related industries (including the testing and evaluation of innovative systems) should be at the heart of new research conducted at regional level, which should be compared and benchmarked nationally and internationally.

The international dimension is indeed crucial and one of the key perspectives of this book. The work presented in these chapters concerns French vineyards and related industries. Given the size of its vine and wine sector, the diversity of its winegrowing areas and wines, and the importance of its research facilities and partners, France is a living lab for the study of adaptation. The country has the potential to make a widespread and global impact, extending its historical influence in the world of wine and its teaching and research. Climate change is affecting all the world's winegrowing areas (chapter II-1), triggering an even wider range of potential initiatives, projects and partnerships. The authors of this book are already involved in European and international projects, and many of their results have been presented at international conferences or under the auspices of the OIV, with scientific partnerships being strengthened. This book seeks to provide the basis for a change of scale by calling for an international interdisciplinary research programme that will continue with the work and methods developed in the LACCAVE project and presented here. Climate change is global, and so is viticulture and wine, albeit with qualities that express local characteristics. If we are to prolong the history of a great plant and drink that express and enrich part of the culture and pleasures of our societies, then adaptive responses to climate change will require greater cooperation and action on a global scale.

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Grapevine is being affected by climate change in many ways, from earlier plant development – which could make vines more vulnerable to spring frosts – to earlier grape ripening.

Increasingly intense extreme weather events, such as heat waves and torrential rain, are also causing major damage to vines. Water stress, which is more pronounced in southern France, has a marked effect on yields. All French vineyards must contend with these issues. Wine characteristics are also changing, with higher alcohol levels, lower acidity and different aromas becoming more common. Meanwhile, new areas are becoming suitable for winegrowing.

The key to addressing these issues is to adapt faster. But how exactly should we do this? What decisions at the local or national level should be taken?

After ten years of research into adapting the French vine and wine industry to climate change, the LACCAVE project, led by INRAE, came to an end in 2021. This book summarizes the results of that project and explores possible levers for action, including new grape varieties; improved soil, water and training system management; reorganization of winegrowing areas; oenological innovations; and new regulations. Readers will find a systemic and strategic vision showing how these actions can be implemented through participatory approaches at different levels, from winegrowers to the winegrowing sector's own climate policy.

This reference book is aimed primarily at industry professionals, lecturers and students.

The French version of this book received the 2024 OIV Award from the International Organisation of Vine and Wine for the Sustainable Viticulture category.

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